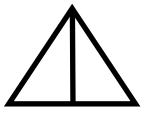

The Dual-Fuel Strategy

An Energy Transition Plan

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Perspective on global warming

- Compelling evidence
- Consensus of expert opinion
- Downside risk is overwhelming
- Risk mitigation is prudent

We need a plan to phase out fossil energy.

Theme

Fuel is crucial in the global energy system.

- Electric power alone is not enough.
- Fuel is also needed.
- Renewable fuels must compete with fossil fuels.
- Hydrogen has failed because it is a *gas.*
- To compete, renewable fuels must be *liquids.*

Energy sources

- Fossil
- Renewable
- Nuclear

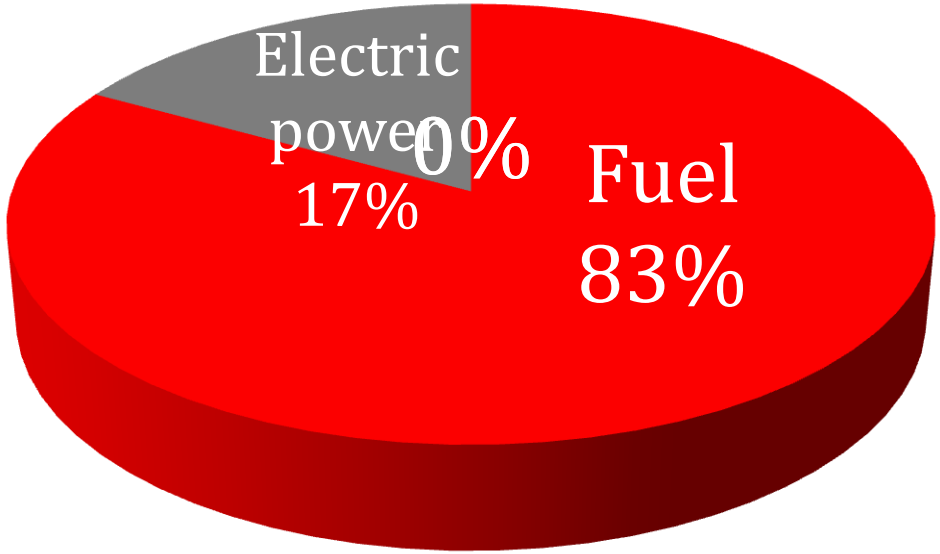
Energy sources are converted to energy vectors to enable trade.

Energy vectors

- Fuel
- Electric power

A vector is an energy carrier that can be bought and sold.

Fuel dominates energy trade



Fuel is crucial in the global energy system. Replacement by electric power with non-fuel storage is unlikely.

Renewable fuel is key

- Fossil → Fuel + Electricity
- Renewable
- Nuclear

} → Electricity

Fossil fuels come *only* from fossil sources.

Transition to renewable sources requires renewable fuels.

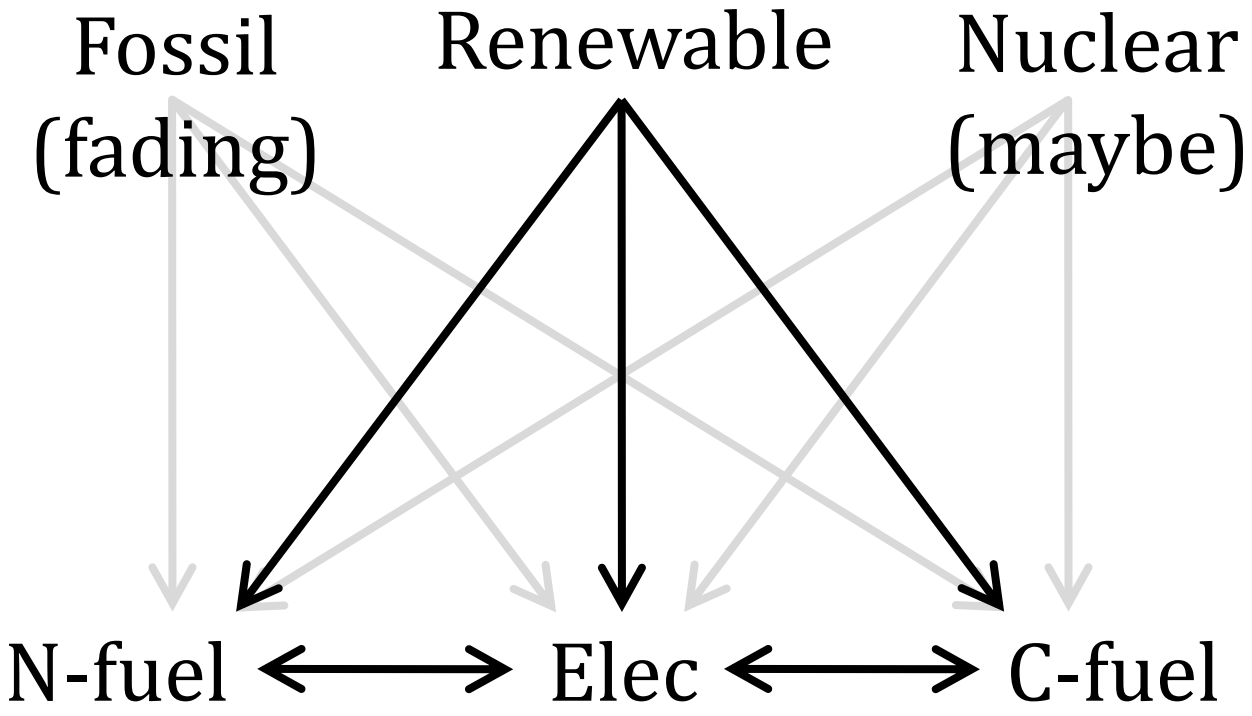
Source-neutral vectors

- Electric power can be produced using any energy source.
- Renewable fuels must also be source-neutral.

Multiple production paths

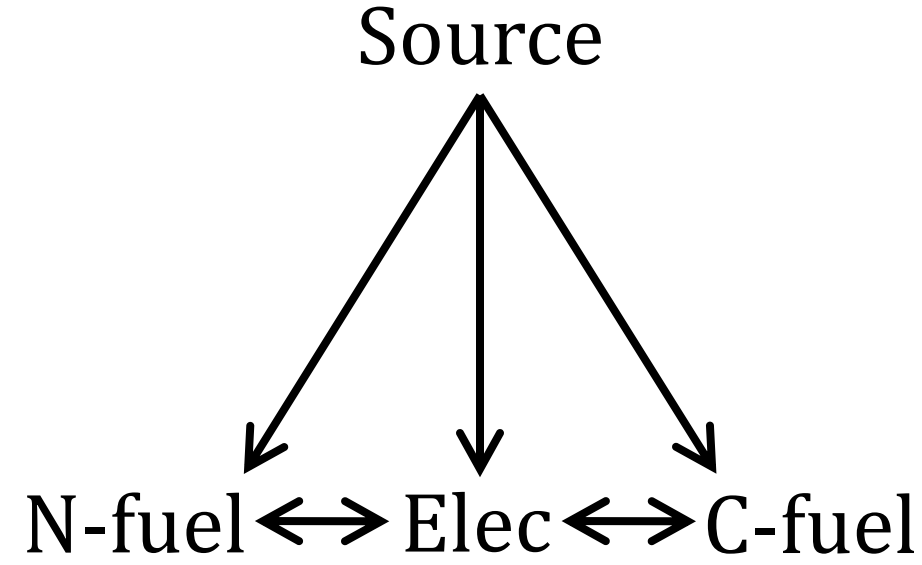
High-efficiency inter-conversion

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

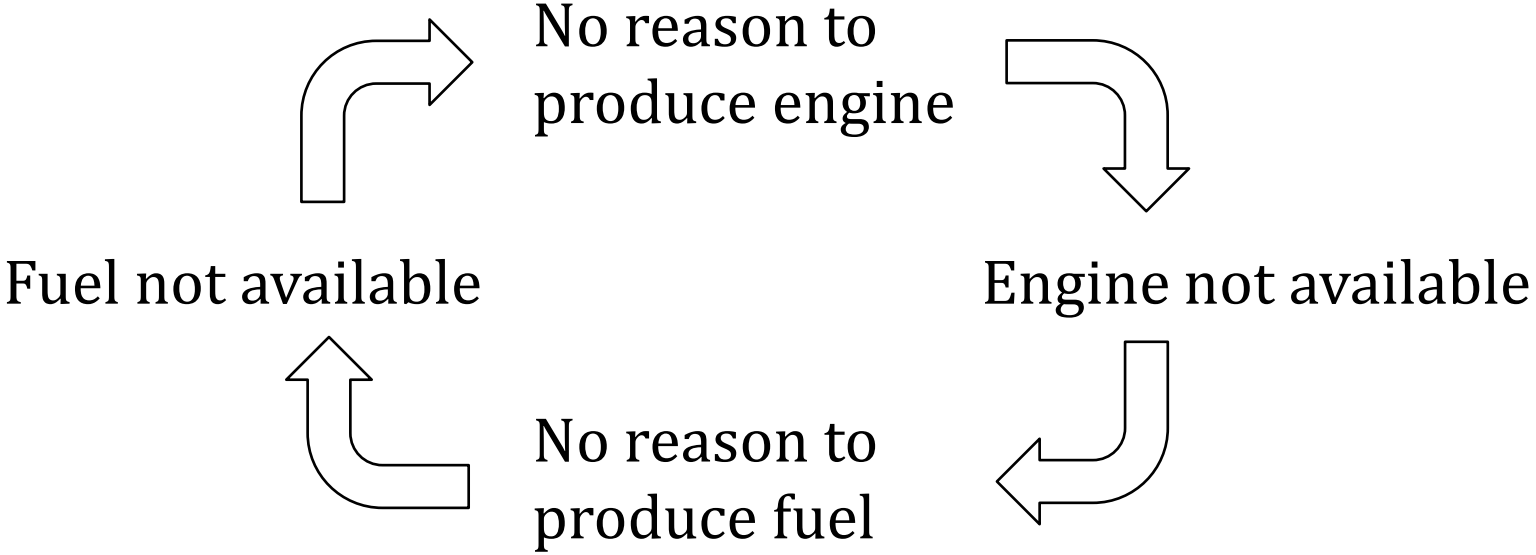
1. EROI
2. Economic inertia

Economic inertia created by legacy infrastructure. To compete, renewable fuels must be compatible.

Legacy infrastructure

- Pipelines
- Tankers—sea, river, rail, road
- Storage—tanks
- Combustors—furnaces and boilers
- Engines—GTs and ICEs

Feedback prevents change

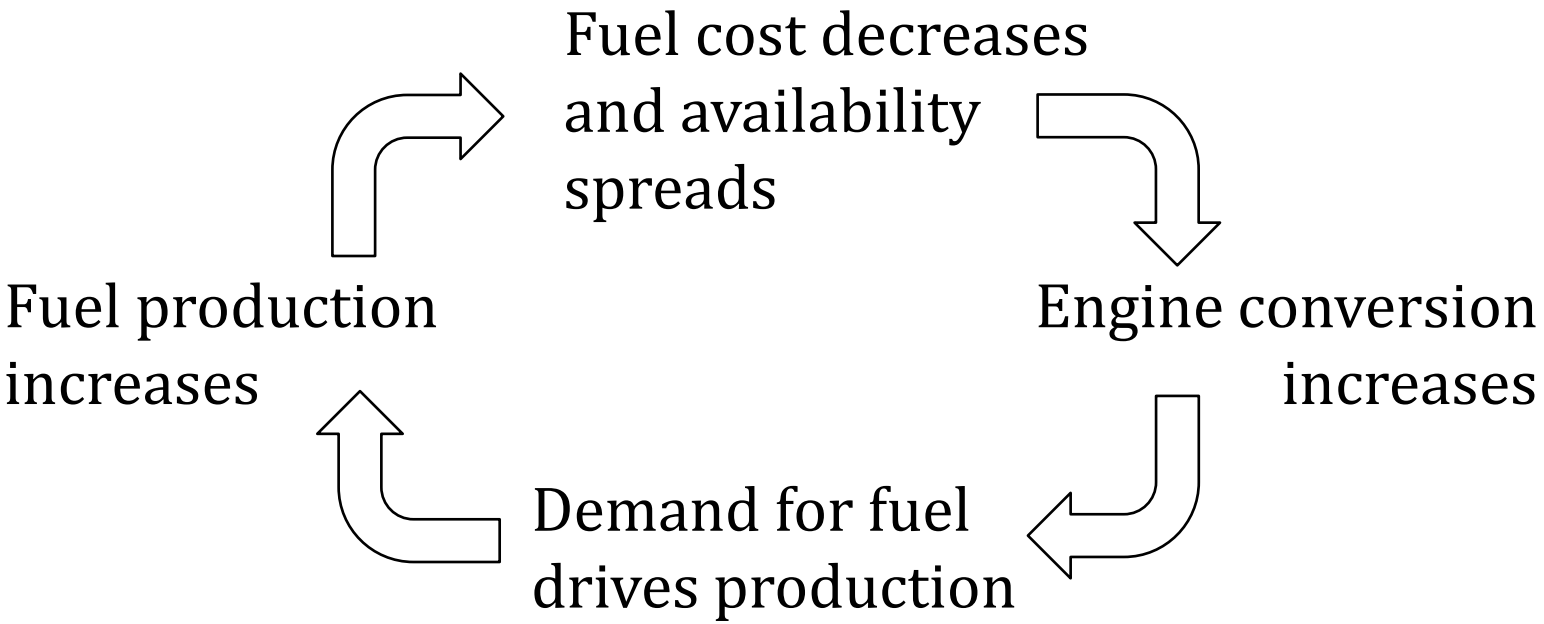


Status quo is stabilized in a <u>vicious</u> cycle: economic inertia.

The key to change

- This is *positive*, not negative feedback
- The system is only *locally* stable
- Strategically applied trigger will cause transition to a *new stable state*

Feedback will enable change



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

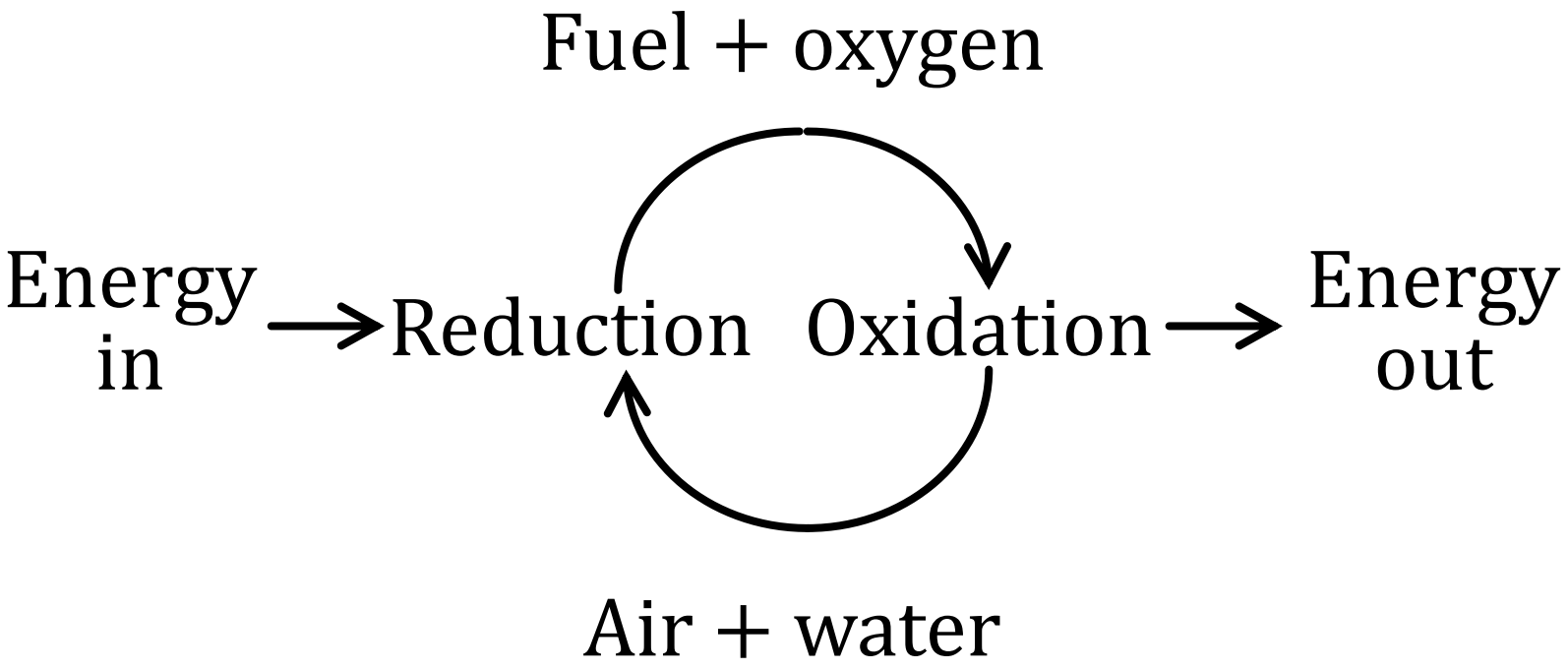
Trigger

Liquid renewable fuels with

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

…compared to competing fuels.

Renewable fuel cycle



Air and water

N_2

O_2

CO_2

H_2O

Renewable fuel options

Reduction
⇄
Oxidation

- Hydrogen $H_2O \rightleftarrows H_2 + \frac{1}{2}O_2$
- Ammonia $\frac{1}{2}N_2 + \frac{3}{2}H_2O \rightleftarrows NH_3 + \frac{3}{4}O_2$
- Methanol $CO_2 + 2H_2O \rightleftarrows CH_3OH + \frac{3}{2}O_2$

State of the Hydrogen Economy

- 40+ years intense effort
- Still no Hydrogen Economy
- Why? Perhaps:

Hydrogen is incompatible with existing infrastructure because it is a high vapor-pressure gas.

Ammonia-methanol dual-fuel pair

- Ammonia is **carbon-free**…

  …but high relative toxicity

- Methanol is **low relative toxicity**…

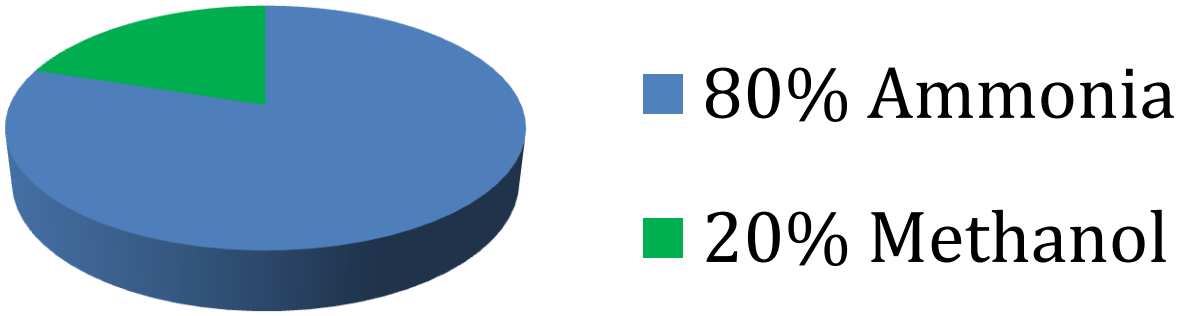
  …but contains carbon

- They are complementary:

  Each has strength to compensate the other's weakness.

Ammonia most, methanol the rest

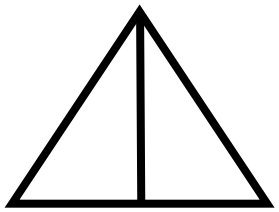
- Ammonia: professional fuel-handlers with equipment and training
- Methanol: when non-professional persons must handle fuel



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 and DME) may be better
  - Key feature: *low relative toxicity*

Dual Fuel Exchange: DFX



A sustainable energy-trade system:

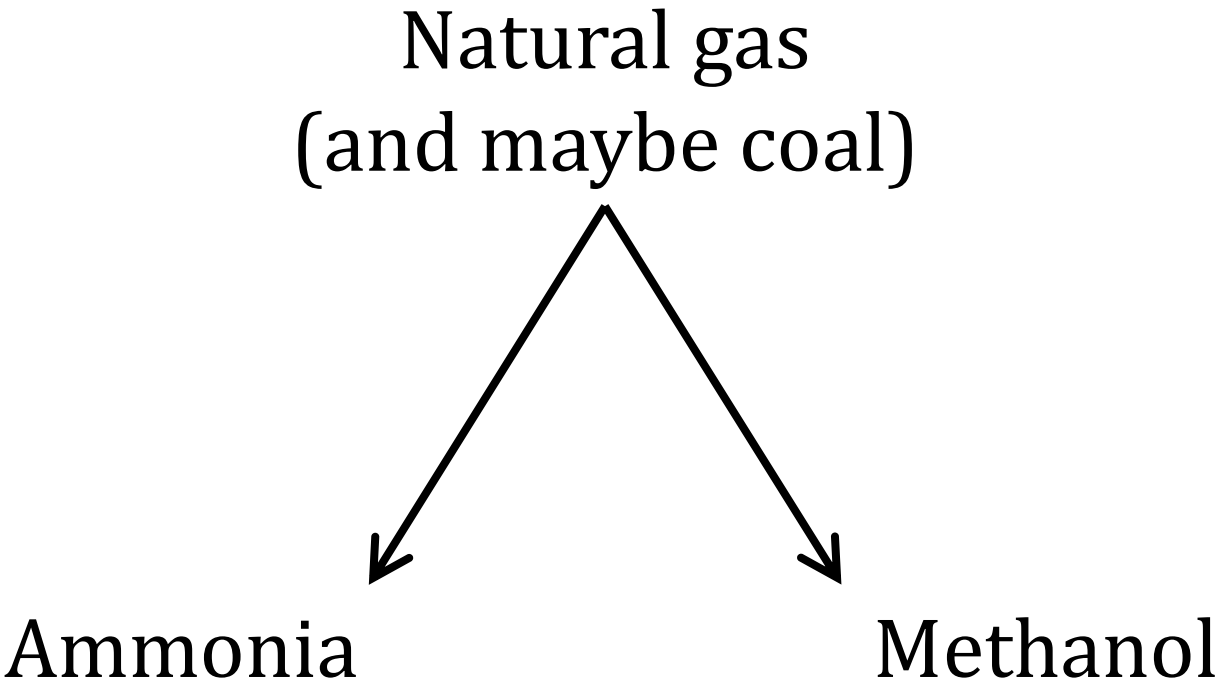
- Two (or few) renewable fuels plus electric power
- Dual use of legacy infrastructure
- Source-neutral fuel production

DFX enables renewable energy sources.

Fuel production

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

Chemical 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

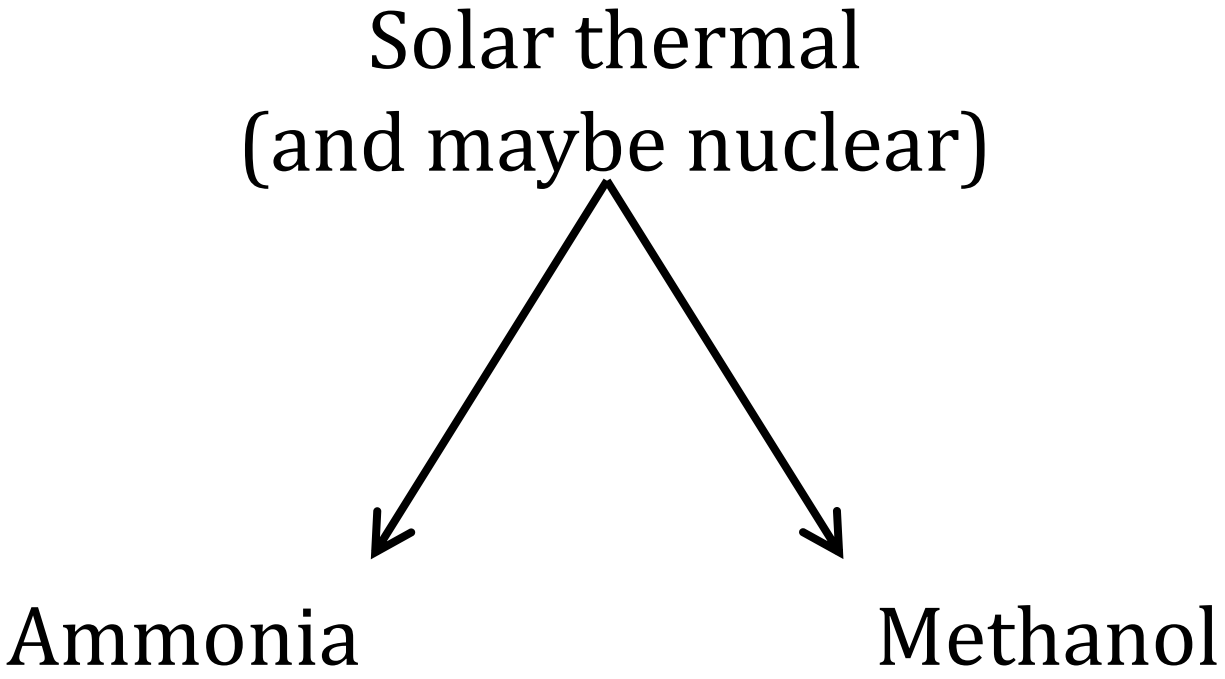
Fuel	P (bar)	Density ($kg \cdot L^{-1}$)	HHV ($MJ \cdot kg^{-1}$)	Energy density ($MJ \cdot L^{-1}$)	Cost per volume ($CN\$ \cdot L^{-1}$)	Cost per energy ($CN\$ \cdot GJ^{-1}$)
Ammonia	10	0.603	22.5	13.6	0.18	**13.3**
CNG	250	0.188	42.5	10.4	0.23	28.2
LPG	14	0.388	48.9	19.0	0.55	28.5
Methanol	1	0.786	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.

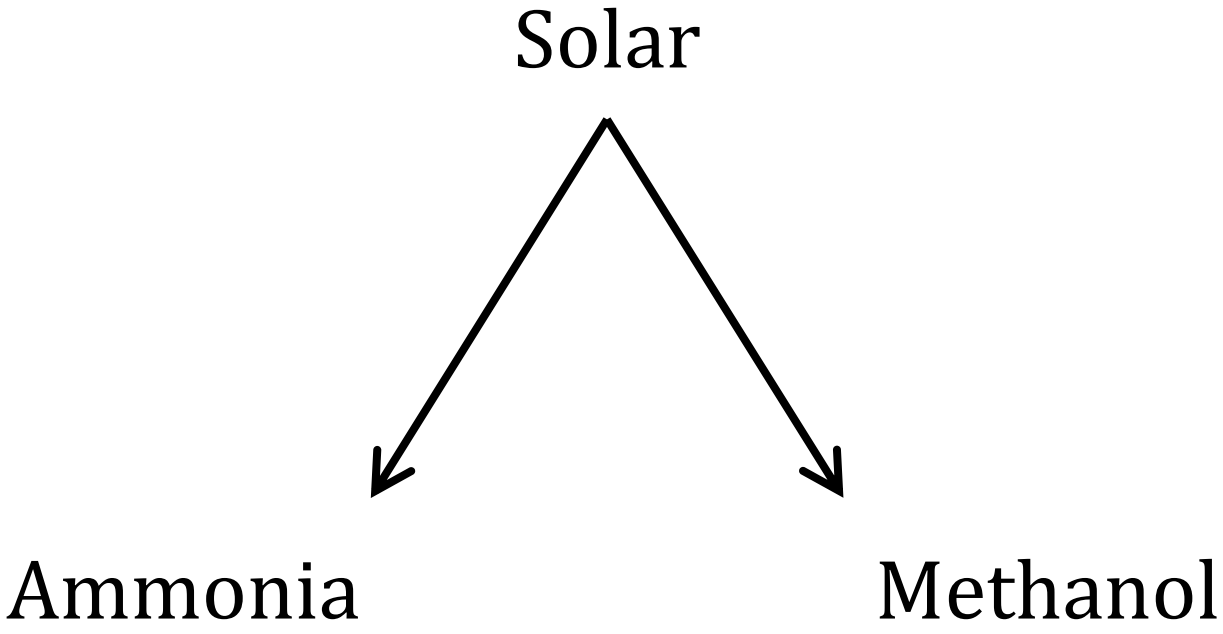
Thermochemical

Direct path from solar thermal and nuclear to renewable fuels.

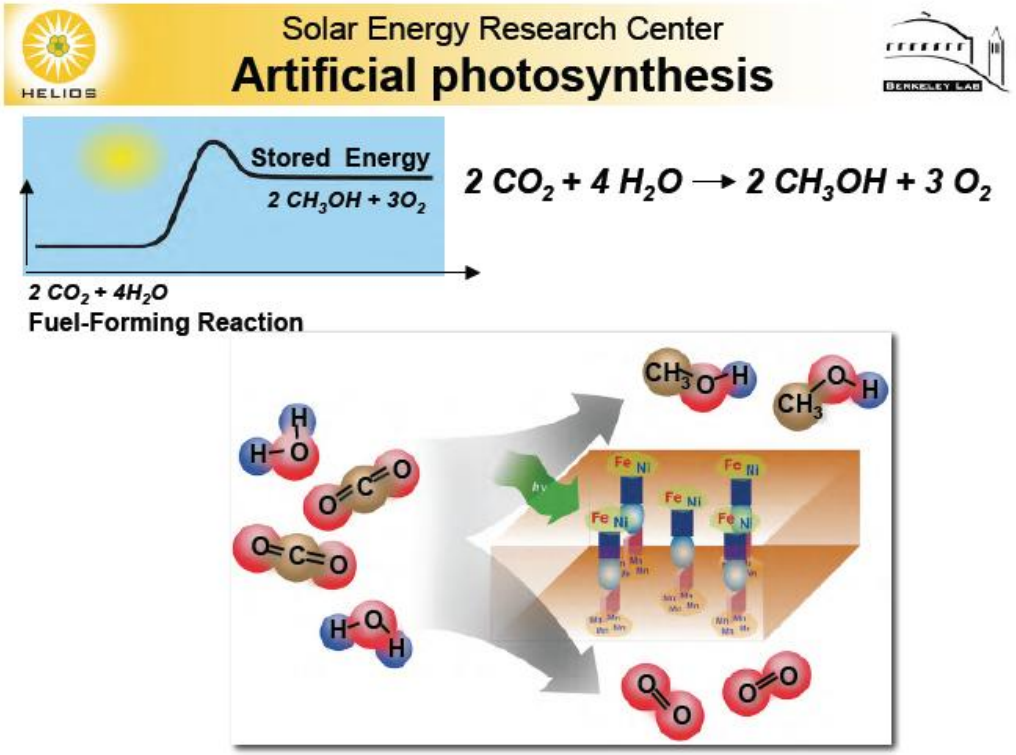


Photochemical

Direct path from solar to renewable fuels.



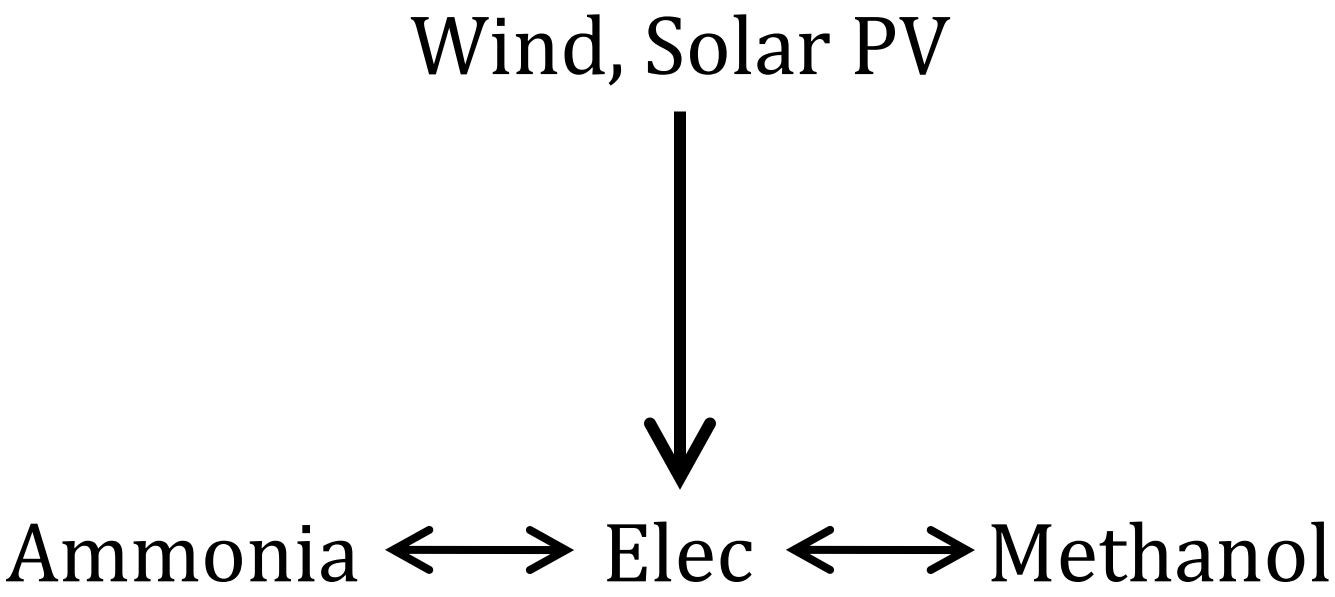
Example from LBNL



Applause!

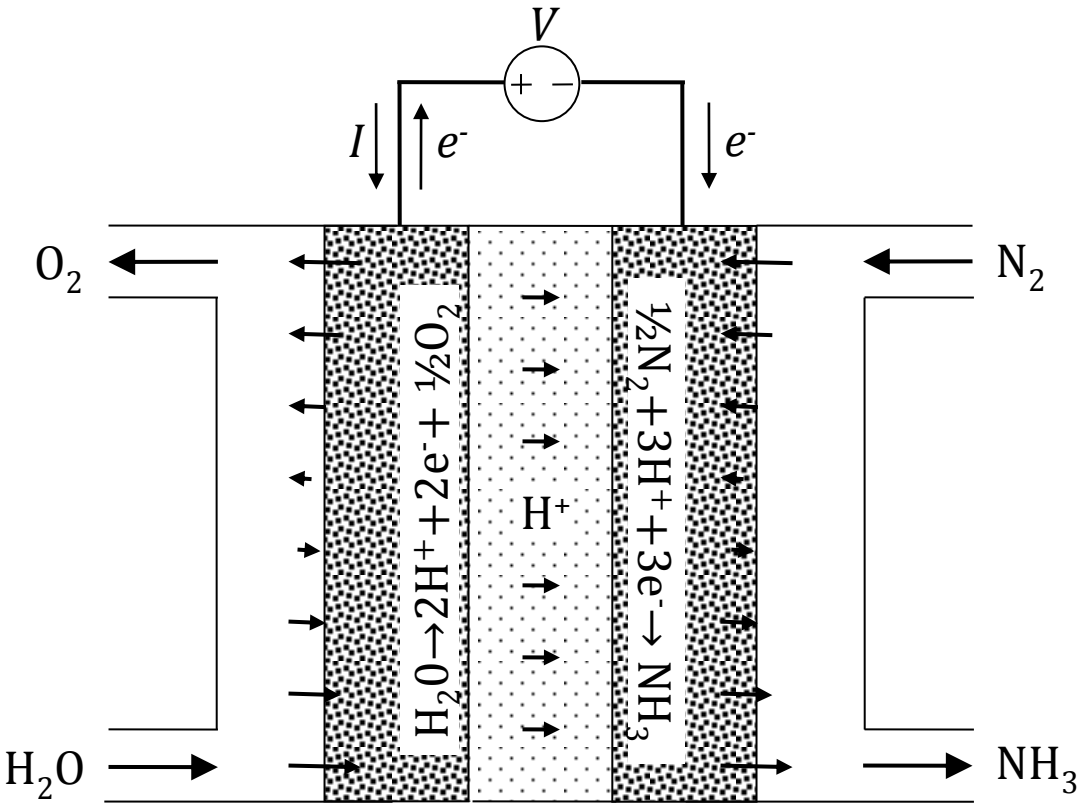
Electrochemical

An indirect path through electric power.



Example: HTEC

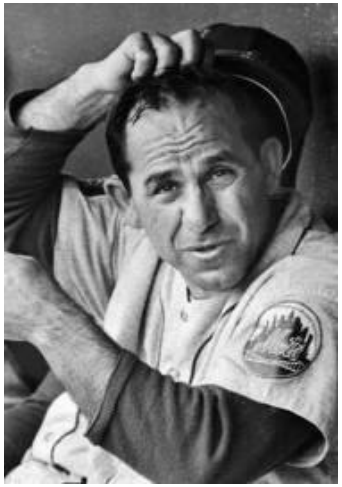
High-temperature electrochemical conversion using proton-conducting solid electrolytes



Efficiency target: 80%

- 80% efficiency each-way conversion of electric power to and from chemical energy (fuel)
- Theoretically possible (?)
- Challenging!
- But imagine: what will happen if this is achieved?

High-efficiency two-way electrochemical energy conversion based on liquid renewable fuels is
DISRUPTIVE TECHNOLOGY.



"It's hard to make predictions…especially about the future."

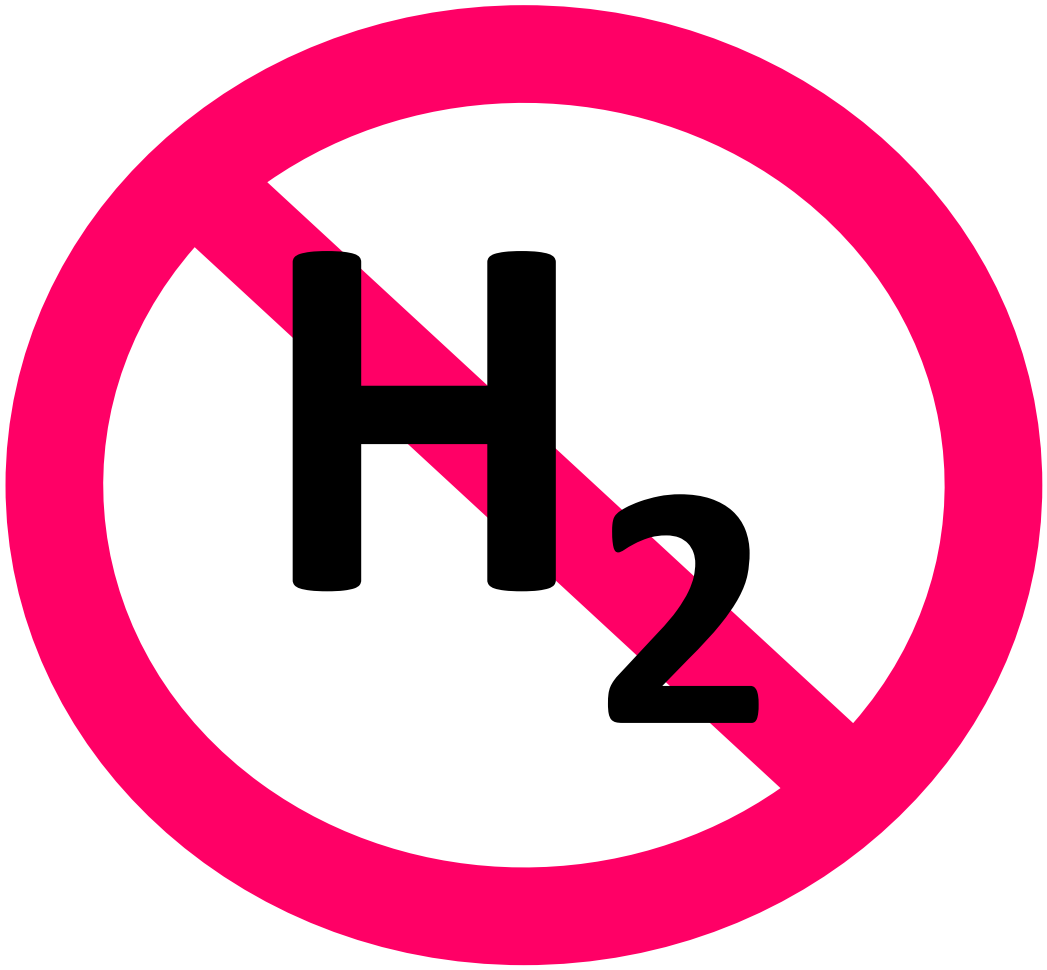
I see liquid renewable fuel in my future. It has higher specific energy than batteries, so my car can be lighter and more efficient. It takes no time to re-charge. It's better than gasoline—low-carbon, stable supply, costs less. How did I ever live without it? It's a solid hit with my old ICE; and with my new electrochemical engine, it's a home run!

—Yogi Berra

could possibly have said that

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


H2

Thank you for your attention.

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In reply to e-mail I will send a 70-page review paper with 170 references.