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 $\rightarrow$ Fuel $+$ Electricity
- Renewable $\rightarrow$ Electricity
- Nuclear $\rightarrow$ 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

- Fossil (fading)
- Renewable
- Nuclear (maybe)

N-fuel ↔ Elec ↔ C-fuel

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

Fuel cost decreases and availability spreads

Fuel production increases

Demand for fuel drives production

Engine conversion increases

Change is driven by a virtuous 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

Fuel + oxygen

Energy in → Reduction → Oxidation → Energy out

Air + water
Air and water

N₂

O₂

CO₂

H₂O
Renewable fuel options

- Hydrogen: \[ H_2O \rightleftharpoons H_2 + \frac{1}{2}O_2 \]
- Ammonia: \[ \frac{1}{2}N_2 + \frac{3}{2}H_2O \rightleftharpoons NH_3 + \frac{3}{4}O_2 \]
- Methanol: \[ CO_2 + 2H_2O \rightleftharpoons CH_3OH + \frac{3}{2}O_2 \]
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

![Pie chart showing 80% Ammonia and 20% Methanol](image-url)
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$_3$OH 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

Natural gas
(and maybe coal)

Ammonia

Methanol
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 CO₂ emissions from ammonia at the point-of-use

⇒ Lower cost delivered to consumer
### Are we there yet?

2009 cost estimates

<table>
<thead>
<tr>
<th>Fuel</th>
<th>P (bar)</th>
<th>Density (kg·L(^{-1}))</th>
<th>HHV (MJ·kg(^{-1}))</th>
<th>Energy density (MJ·L(^{-1}))</th>
<th>Cost per volume (CN$·L(^{-1}))</th>
<th>Cost per energy (CN$·GJ(^{-1}))</th>
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<td>Ammonia</td>
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<td>22.5</td>
<td>13.6</td>
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<td>CNG</td>
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<td>LPG</td>
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<td>Methanol</td>
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<td>Gasoline</td>
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<td>142</td>
<td>3.6</td>
<td>0.10</td>
<td>28.2</td>
</tr>
</tbody>
</table>

1 gal = 3.8 L

Thermochemical

Direct path from solar thermal and nuclear to renewable fuels.

Solar thermal
(and maybe nuclear)

Ammonia               Methanol
Photochemical

*Direct path from solar to renewable fuels.*

Solar

- Ammonia
- Methanol
Example from LBNL

Applause!

2 CO₂ + 4 H₂O → 2 CH₃OH + 3 O₂
Electrochemical
An indirect path through electric power.

Wind, Solar PV

Ammonia ↔ Elec ↔ Methanol
Example: HTEC
High-temperature electrochemical conversion using proton-conducting solid electrolytes

\[ \text{H}_2\text{O} \rightarrow 2\text{H}^+ + 2\text{e}^- + \frac{1}{2}\text{O}_2 \]

\[ \frac{1}{2}\text{N}_2 + 3\text{H}^+ + 3\text{e}^- \rightarrow \text{NH}_3 \]

\[ \text{O}_2 \quad \text{N}_2 \quad \text{H}_2\text{O} \quad \text{NH}_3 \]
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.
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 its own flaw that has historically discouraged development
• Together, they are a superior alternative to hydrogen
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.