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
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*
Source and vector are distinct!

- Oil and natural gas are fossil *sources* that are often used to make fossil *fuels*
- But they can also be used to make *renewable* fuels
- Natural gas is used to make hydrogen, ammonia, and methanol
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
• E.g. three vectors:
  – Electric power
  – Nitrogen-based fuel: N-fuel
  – Carbon-based fuel: C-fuel
Sustainable global energy system

Highly interconnected source-vector network makes for stable supply at low cost
Nuclear, maybe

- Subsequently I use “Renewable” as short-hand for “Renewable and maybe nuclear.”
- Nuclear energy might play a role.
  - Fusion
  - Safe and sustainable fission, e.g. Liquid Fluoride Thorium Reactor (LFTR)*
- If so, plants will be sited remotely from population centers.
- Energy must be stored and transported as fuel.

* Web site: Energyfromthorium
All energy trade is carried by two (or few) renewable fuels plus electric power, inter-convertible with each other.
Fossil-free energy

Renewable

N-fuel ↔ Elec ↔ C-fuel

Renewable (and maybe nuclear) sources generate electric power used to produce renewable fuels
And/or...

Renewable

N-fuel → Elec ← C-fuel

*Direct conversion to fuels; subsequent conversion to electric power for use.*
Solar is the big energy resource

- Rooftops might supply 10% of global energy
- The rest must come from energy farms
- All sizes, located everywhere
- Very large energy farms will be built in remote deserts and oceans

Transport and storage of renewable or nuclear energy captured in remote energy farms will be accomplished using liquid renewable fuels
All we need is 2% of Earth surface

Adapted from Nate Lewis, *Powering the Planet*. 
Fossil fuels are hard to displace

1. EROI – falling
2. Economic inertia

*Economic inertia created by legacy infrastructure. To compete, renewable fuels must be compatible—liquids!*
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.
Feedback will enable change

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
Strategy

• First produce renewable fuels from natural gas and perhaps coal. Compared to oil:
  – Stable supply
  – Half-price per energy unit
• Create market demand for renewable fuels
• Demand stimulates innovation and investment in production from renewable sources
• Cost of production from renewable sources goes down
• Renewable sources then displace fossil sources
We need liquid renewable fuels. What are they?
Renewable fuel cycle

Fuel + oxygen

Energy in → Reduction → Oxidation → Energy out

Air + water
Air and water

$\text{N}_2$

$\text{O}_2$

$\text{CO}_2$

$\text{H}_2\text{O}$
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*
Better alternatives?

• *Nitrofuel* is nitrogen-based renewable fuel
  – NH₃ is the simplest example
  – Liquid ammoniates (e.g. Divers’ solution) may be better
  – Key feature: *zero (or low) carbon*

• *Carbofuel* is carbon-based renewable fuel
  – CH₃OH is the simplest example
  – Others (e.g. EtOH, DME, CNHCs) may be better
  – Key feature: *low relative toxicity*
  – CNHCs offer *high energy density*
N-fuels cost less than C-fuels

Air 78% N₂ ⇒ N-fuels are low cost
Air 0.04% CO₂ ⇒ C-fuels are high cost

$ NH₃ – low energy density/professional handlers
$$ CH₃OH – low energy density/nonprofessional
$$$ CNHCs – when high energy density is mandatory

Use NH₃ when possible; CH₃OH when necessary; CNHCs when essential.
Highest cost: CNHCs

*Carbon-Neutral Hydrocarbons*

- Examples:
  - higher alcohols (e.g. butanol)
  - higher alkanes (e.g. octane, dodecane, hexadecane)
- Produce from air-derived synthesis gas or methanol
  - E.g. Fisher-Tropsch or Mobil MTG processes
- Direct replacement for fossil fuels
- High energy density and also high cost

*Use when energy density justifies cost*
  - e.g. aviation (perhaps)
Nitrogen-based fuel meets most needs

“20% other” includes:

• Methanol for non-professional highway transport
• CNHCs for high-energy density (e.g. aviation)
Ammonia issues

- Inhalation hazard
- Fire/explosion advantage
- Environmental risks
- NOx
Personal Protective Equipment (PPE) Requirements For Ammonia

- **REQUIRED**
  - Rubber Gloves
  - Eye Protection

- **RECOMMENDED**
  - Face Shield
  - Long Sleeve Shirt
Mandatory training every two years

A Guide for Developing a Training Program for ANHYDROUS AMMONIA WORKERS
Safety advantage of NH$_3$

*Low fire/explosion hazard*

- NFPA/DOT class “non-flammable”
- Anomalously high minimum ignition energy (MIE) in air
- Ideal fuel for fire/explosion safety:
  - Can be ignited in a combustor
  - Very difficult to ignite accidentally
  - Lighter than air—rises and disperses
  - Flame extinguished by water
Environmental risks

$NH_3$ spill effects are intense but short-lived

- Ammonia in high concentration is toxic
- In low concentration, it’s fertilizer
- Spills disperse and self-remEDIATE relatively quickly compared to oil
- Nitrification is a risk—mitigation is required
- $NH_3$ is inferior to $H_2$ in this category, but $H_2$ has other issues ...

There is no perfect fuel; all have pros and cons – assess choices relative to each other
NOx

• Thermal NOx comes from heating air; forms no matter what fuel—even hydrogen
  \[ \text{N}_2 + \text{O}_2 + \text{heat} \rightarrow 2\text{NO} \]

• Fuel-bound nitrogen can form NOx more easily; single vs. triple bond to break

• Both controlled by kinetics not thermodynamics

• Both suppressed by combustion engineering

• True for any fuel, including ammonia
Thermal de-NOx

\[ \text{NH}_2 + \text{NO} \rightarrow \text{N}_2 + \text{H}_2 \text{O} \]

- NH\(_3\) injected after burner to suppress NOx
- NH\(_2\) radicals act as scavenger
- Invented mid-seventies—Exxon patent
- Now used in most fossil-fueled electric power plants, which have ammonia on-site

*Low-NOx ammonia combustion is possible but requires careful engineering*
Fuel production

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

Current low-cost standard for production of ammonia and methanol

Natural gas
(or coal or oil)

<table>
<thead>
<tr>
<th>Ammonia</th>
<th>Methanol</th>
</tr>
</thead>
</table>

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 ↔ Electric power ↔ Methanol
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.
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*
Competitive advantage

*Liquid renewable fuels vs. oil-derived fuels*

- **Agile production**
  - Source-neutral
  - Low-cost, stable supply

- **Legacy compatibility**
  - Renewable fuels, like current fossil fuels, are *liquids*
  - Low investment barrier to adoption

- **Risk mitigation**
  - Global warming
  - Regulatory actions
Strategy

• To begin, market renewable fuels produced at low-cost from fossil sources
• Identify trigger markets in which renewable fuels can best compete
  – Maximum benefit from stable supply at low cost with low carbon footprint
  – Minimum infrastructure investment barrier
• Grow market for renewable *fuels*
• Transition to renewable *sources* as technology develops enabling low cost
Renewable fuels from fossil sources

- Standard practice today
- GTL/CTL 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
- Stranded NG can be monetized
- Safety advantage—low explosion hazard
- Carbon advantage—no CO$_2$ emissions from ammonia at the point-of-use

⇒ Lower cost delivered to consumer
## Half-price threshold is within reach

### 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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<tbody>
<tr>
<td>Ammonia</td>
<td>10</td>
<td>0.603</td>
<td>22.5</td>
<td>13.6</td>
<td>0.18</td>
<td>13.3</td>
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<td>CNG</td>
<td>250</td>
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<td>42.5</td>
<td>10.4</td>
<td>0.23</td>
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<td>LPG</td>
<td>14</td>
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<td>48.9</td>
<td>19.0</td>
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<td>Methanol</td>
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<td>Hydrogen</td>
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<td>0.025</td>
<td>142</td>
<td>3.6</td>
<td>0.10</td>
<td>28.2</td>
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</tbody>
</table>


Hydrogen storage as metal hydride is assumed. Methanol specific energy restored from reformer-adjusted to true value.
Trigger markets for ammonia

- Base load electric power; especially near existing ammonia pipelines
- Energy hubs; CCHP (trigeneration)
- Rail and marine propulsion; trains and ships can carry enough fuel for long trips with them

*These applications employ professional fuel handlers*
U.S. ammonia infrastructure

Ray Hattenbach, Chemical Marketing Services Inc., 2006
Gigawatt power generation
Replace natural gas with ammonia

- Only the boiler needs modification
- Ammonia is already familiar to power plant operators (thermal denox)
DG–CCHP
Distributed Generation with Combined Cooling Heat and Power

High efficiency electric power generation by utilizing otherwise wasted heat.
Energy hubs

Power and energy paradigm for the 21st century

- Energy hubs both *produce* and *consume* energy; trade between hubs to balances production/consumption
- Very high efficiency is achieved by DG-CCHP (DTG: Distributed Tri-Generation)
- Trade between hubs is carried by *both* electric power and renewable fuels; new “Grid” is a network for both
- Some hubs *produce* fuels, others only consume
- Energy moves by land in wires and pipes (or river, rail and road tankers) and by sea in tanker ships
- Energy is stored as liquid renewable fuels in low-cost tanks, *definitely solving the storage problem for renewable sources*
Fuel power density

Figure of merit for pipeline transport of fuels

\[ F = \rho h \sqrt{h} \]

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>( M )</th>
<th>( p )</th>
<th>( \rho )</th>
<th>( h_H )</th>
<th>( h_L )</th>
<th>( \rho h_L )</th>
<th>( \sqrt{h_L} )</th>
<th>( F )</th>
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<tr>
<td>Hydrogen</td>
<td>( \text{H}_2(g) )</td>
<td>2.02</td>
<td>50</td>
<td>4.06</td>
<td>141.80</td>
<td>120.97</td>
<td>0.49</td>
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<td>Methane</td>
<td>( \text{CH}_4(g) )</td>
<td>16.04</td>
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<td>1.79</td>
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<tr>
<td>Ammonia</td>
<td>( \text{NH}_3(l) )</td>
<td>17.03</td>
<td>10</td>
<td>681.90</td>
<td>22.50</td>
<td>18.65</td>
<td>12.71</td>
<td>4.32</td>
<td>54.90</td>
</tr>
</tbody>
</table>

Ammonia is 5\times better than natural gas and 10\times better than hydrogen
Pipes vs. wires
Low-cost transport by sea

Monetize stranded natural gas.
West coast port facilities

**LNG**
- Ensenada - Energía Costa Azul

**Ammonia**
- Portland – J.R. Simplot
- Sacramento - Agrium
- Stockton - Calamco
Near-term CO$_2$ reduction

Enable CCSS by concentrating CO$_2$ at a few large sources
California

5 gas fields

390 gas power plants
Marine propulsion

• Ammonia is shipped in tankers
• Why not use it to propel the ship that carries it?
• Why not use it to propel other ships?
Ammonia as fuel for ships

- Distribution relatively easy
  - Ships travel long distances between re-fueling
  - Need only a few marine fuel terminals
  - Low energy density not a major problem—bigger fuel tanks (relatively easy to make bigger ships) or more frequent rendezvous with tenders

- Low pollution
  - NOx can be suppressed (R&D needed)
  - No SOx, CO, CO₂, soot, etc.
  - Small spills rapidly remediated by natural processes—NH₃ is a nutrient in small doses

- Enhanced survivability for warships
  - Fuel supply difficult to ignite
  - If ignited, fire is easily extinguished with water
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
Thank you for your attention

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In reply to e-mail I will send a 96-page working paper with 285 references