Opportunities and Pathways to a Green Future for All
(based on a Chinese Academy of Sciences report of the same title)

Choon Fong Shih
University Professor and Advisor
National University of Singapore
University of Chinese Academy of Sciences

“Opportunities and Challenges for Methanol as a Global Liquid Energy Carrier”
Stanford University, July 31st – August 1st 2017
TWO FUTURES

Business as Usual

Green Future for All

Fossilized Sunshine

Liquid Sunshine

*Image credit: Foreign Policy, the Global Magazine of News and Ideas, May 31st 2017*
Business as Usual or Green Future?

Common man solution for our common destiny

CO₂ emissions abatement by Non-OECD countries is key to our Green Future

Annual CO₂ Emissions from Energy Use

Today

CO₂ emissions abatement by OECD countries alone make little difference

OECD

Non-OECD

95GT/year by 2100

Sources: Data from ‘BP Statistical Review 2016’ for data up to 2015.

Optimistic target based on abating about 2.5 trillion tons of CO₂ over the next 80 years, vis-à-vis Business as Usual.
Pathways to Sustainable Green Future

Fossilized Sunshine
1G – 2G
Fossil Methanol

Hybrid Systems
3G – 4G
Clean Methanol

Liquid Sunshine
5G & beyond
Green Methanol

Today
2020
2040
2050
2070

Hybrid Systems
First Deployment
Mass Deployment

Liquid Sunshine
First Deployment
Mass Deployment
Energy is Humankind’s Biggest Challenge!

Three Existential Threats

1. Climate change
2. Environment degradation
3. Depleting fossil fuels

World Pop.
- 1720: 0.6 B
- 1870: 1.3 B
- 2020: 7.6 B
- 2050: >9 B
- 2200: ??

Coal: 150 more years
Oil: 100 more years
Renewables: "Fossilized Sunshine"

Energy is Humankind’s Biggest Challenge!
Rising Pollution & Population Plummeting Resources

OECD Countries

15.2
PM2.5 μg/m³

1 : 3

Non-OECD Countries

44.1
PM2.5 μg/m³

Local Environment Degradation

Rising Pollution & Population
Plummeting Resources

Depleting Fossil Fuel Reserves

Fossil Fuel Reserves (toe/capita)

World Population (millions)

Fossil Fuel Reserves (LHS)  World Pop (RHS)
Plentiful Sunshine!

Can Saudi Arabia export sunshine to every corner of the World? HOW?
Sunshine is Vast Inexhaustible Resource

1 hour of Sunshine > 1 year of global energy needs

Challenge: Turning Sunshine into an energy commodity distributable worldwide
Common Man Solution for Our Common Destiny

What are the ways to ...

Harvest Sunshine?

Convert & Store?

Transport & Distribute?

Environmental Impact? What can we learn from nature?

The WORLD’s fossil fuels are depleting fast ...
Designing Energy Carrier & System Inspired by Nature
Ecologically Balanced Cycle

Plentiful Sunshine

Harvest

Conversion & Storage
stable chemical form

Distribution
liquid-based systems

Utilization

Recycle

Energy Transporter
CO₂ + H₂O*

CO₂ and H₂O are nature’s energy transport agents that bind and store the sun’s energy in chemical form; they are recycled to the environment when the chemical energy is utilized.
Fossil Fuel-based Energy System
Extracting fossil fuels and dumping CO₂ and pollutants into atmosphere

From the bowels of the Earth

Conversion & Storage
Fossil Fuels
Distribution
Utilization

Atmospheric Dump
CO₂ & Pollutants

Depleting Fossil Fuel Reservoir

To the atmosphere of the Living Earth

Organic & Inorganic Matter
Battery-based Energy System

Extracting lithium, etc., and dumping battery waste into landfills

Plentiful Sunshine

Harvest

Conversion & Storage

Energy Transporter Batteries

Distribution

Utilization

Material Pathway

Depleting Mineral Mines

Battery Factory

From the bowels of the Earth

To the land of the Living Earth

Battery Dump
Comparing Carriers of Green Energy
Liquids are Optimal Medium to Store and Transport Energy

<table>
<thead>
<tr>
<th>Energy Physical State</th>
<th>Solid</th>
<th>Liquid</th>
<th>Gaseous</th>
<th>Electro-chemical†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Carrier</td>
<td>Biomass</td>
<td>Alcohols</td>
<td>Hydrogen</td>
<td>Battery/Electricity</td>
</tr>
<tr>
<td>Energy Density</td>
<td>🔺</td>
<td>🔺</td>
<td>🔺</td>
<td>🔺</td>
</tr>
<tr>
<td>Storage Costs</td>
<td>🔺</td>
<td>🔺</td>
<td>🔺</td>
<td>🔺</td>
</tr>
<tr>
<td>Transport Costs*</td>
<td>🔺</td>
<td>🔺</td>
<td>🔺</td>
<td>🔺</td>
</tr>
<tr>
<td>Environmental Impact^</td>
<td>🔺</td>
<td>🔺</td>
<td>🔺</td>
<td>🔺</td>
</tr>
</tbody>
</table>

**Observations**
- Liquids are optimal for storing and transporting energy
- E.g. Natural gas is turned into LNG for shipping globally
- Alcohols are stable energy-dense medium for storing electricity and hydrogen at ambient conditions

* Long distance transportation/shipping > 5,000km
^ Includes pollution from production, use, and disposal
† Electricity must be used as it is generated or converted immediately into storable forms, e.g. electrochemical energy stored by batteries
Reservoirs Enable Man to Control and Manage Nature’s Intermittent Resources

Once stored in reservoirs, resource can be distributed and drawn on demand within the control of humankind.
Energy Carriers – Sweet-Spot

Uncompressed Gas*

Highly Compressed Gas*

*Excluding weight of heavy gas tanks

Sweet-Spot
high energy density by weight & volume

Liquid†

Directional target of preferred energy carriers

Batteries

Redox flow

Li-ion

Liquids occupy the energy density sweet spot; they are also stable, easy to store, transport, distribute. Methanol has, on a volume basis, 40% more H₂ than liquid hydrogen at -253°C, and 140% more H₂ than compressed hydrogen at 700 bars.
Battery, Hydrogen & Alcohol Energy Reservoirs
Reservoir size for 3 hours storage of global energy needs in 2050

**How Large?**
Stacked on top of a 7,140 m² football field

- Li-ion Batteries: ~3x
- Compressed Hydrogen at 700 bars: ~1.7x
- Compressed Hydrogen at 200 bars: 0.3x

**How Heavy?**
Weight in thousands of Airbus A380s

- Li-ion Batteries: ~30x
- Compressed Hydrogen at 700 bars: ~1.5x
- Compressed Hydrogen at 200 bars: ~10x
- Alcohol Fuels: 60

**Li-ion Batteries:**
12 mil tonnes of Lithium (86% of world's reserves) required upfront, 10-15% add-on per year; massive hazardous waste

**Compressed H₂:**
Very small molecule and prone to leakage; large-scale storage of compressed hydrogen could pose serious safety risks

**Alcohol Fuels:**
Alcohol fuels such as methanol and ethanol have high energy density by weight and by volume
Battery, Hydrogen and Methanol
Estimated cost of distribution infrastructure

**Methanol**
- Retrofit trucks, tanks and pumps

**Hydrogen**
- CFRP Tanks for transport, storage

**Battery**
- Grid upgrades, new charging stations

**Distribution: Wholesale to End-Users**

**Infrastructure Costs**
- **Methanol**: $10-15 billion
- **Hydrogen**: ~300x
- **Battery**: ~100x

* Estimated upfront infrastructure costs, assuming 200 cars per 1000 people, for China, in the next decade

^ Methanol is the simplest and easiest target of green liquid fuels
### Energy Carriers/Sources – Key Pollutants

<table>
<thead>
<tr>
<th>Resource</th>
<th>Structure and Constituents</th>
<th>CO₂</th>
<th>Major Pollutants (NOₓ, SOₓ, PM)</th>
<th>Storage, Shipping, Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>Complex mixture of organic and inorganic compounds, heavy metals. Various coal grades have differing nitrogen &amp; sulfur content.</td>
<td>100</td>
<td>NOₓ 100, SOₓ 100, PM 100</td>
<td>Semi Global</td>
</tr>
<tr>
<td>Crude Oil</td>
<td>Complex mixture of compounds, consisting primarily of C₅ to C₇₀ hydrocarbons. Sulfur content varies greatly.</td>
<td>76</td>
<td>NOₓ 93, SOₓ 100, PM 60</td>
<td>Global</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>Predominantly CH₄. Some C₂H₆ and other light hydrocarbons.</td>
<td>40</td>
<td>NOₓ 2, SOₓ 69, PM 3</td>
<td>Regional</td>
</tr>
<tr>
<td>Methanol* (C1 Alcohol)</td>
<td>Simplest alcohol fuel, CH₄O</td>
<td>45</td>
<td>NOₓ 34, SOₓ 0, PM 0</td>
<td>Global</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>Hydrogen is gaseous above -253°C, It is liquefied or pressurized to 700 bars for storage purposes.</td>
<td>0</td>
<td>NOₓ 70, SOₓ 0, PM 0</td>
<td>Highly Restricted</td>
</tr>
</tbody>
</table>

*These data would also apply to ethanol, a C₂ primary alcohol. Methanol and Ethanol occupy the sweet spot of being both clean and easy to store, ship and distribute.

Estimated data based on (i) empirical results for power generation per unit output and (ii) emissions standards for boilers.
Fossil-based Electricity and Oil
Shaped today’s world, but not much longer

Clean at point of use
Instant, on-demand power
Versatile with many applications

High energy density
Feedstock for materials
Stable, storable and transportable

Looming threats of fossil-based energy: Environmental Impact, Depleting Resources
Green Electricity and Green Liquids

- **Electricity**
  - instant multipurpose power & no emissions at point of use

- **Surplus Power**

- **Green Synergistic Dual Energy System**

- **Liquid storage**
  - versatile, easy to store & ship with global reach

- **Regenerate Electricity**

- **Can leverage existing extensive energy infrastructure**

- **Green Electricity and Green Liquids** can leverage existing extensive energy infrastructure

- **Light / AC**, **Appliances**, **Mobile gadgets**, **Transportation**, **Machinery**, **Materials**

- **Instant multipurpose power & no emissions at point of use**

- **Versatile, easy to store & ship with global reach**
Life Cycle Approach
Energy and Material Pathways

Well-to-Wheels

Before POU

Energy Extraction, Conversion & Distribution

Well-to-Tank

Utilization

Efficiency entails both POU and before POU

Cradle-to-Grave

Vehicle Production

Point of Use (POU)

Tank-to-Wheels

Disposal
# Battery Cars Are Clean “No Emissions”

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>CO$_2$ g/km</th>
<th>Pollutants mg/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before Point of Use</td>
<td>390</td>
<td>80</td>
</tr>
<tr>
<td>LNG to Gas to BEV*</td>
<td>310</td>
<td>135</td>
</tr>
<tr>
<td>Coal to BEV*</td>
<td>300</td>
<td>135</td>
</tr>
</tbody>
</table>

# Gasoline Cars Are Dirty

<table>
<thead>
<tr>
<th>Pollutants</th>
<th>CO$_2$ g/km</th>
<th>Pollutants mg/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before Point of Use</td>
<td>210</td>
<td>245</td>
</tr>
</tbody>
</table>

**Note:**
- BEV = Battery-electric vehicle
- Battery disposal not included
Batteries are also Costly
Breakeven economics and end-of-life recycling costs

Recycling assumption: Net cost of battery recycling assumed to be $150/kWh in 10 years
Hydrogen Distribution is Very Costly
Conversion costs from gasoline/diesel refueling systems

**Methanol**
(simplest alcohol fuel)
USD 25k

**Hydrogen**
* New hydrogen storage equipment requires large amount of space
USD 1.5 – 2 million
Hydrogen pump plus array of storage tanks for ~15 cars

† Includes retrofitting of nozzle, pump and storage tanks

Storage at 700+ bars
Applying 3E Criteria to current and alternative energy solutions

There is no perfect energy solution, only optimally-balanced energy solutions
## 3E Assessment Across The Life Cycle

**Light vehicles (comparing technologies)**

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline ICEV</td>
<td>Conventional Gasoline Car</td>
</tr>
<tr>
<td>Coal to BEV*</td>
<td>Battery Electric Vehicle powered by Coal-power</td>
</tr>
<tr>
<td>NG to BEV*</td>
<td>Natural gas (NG) imported as LNG to produce power for Battery Electric Vehicle</td>
</tr>
<tr>
<td>Methanol ICEV</td>
<td>Natural gas converted to Methanol, Combustion engine</td>
</tr>
<tr>
<td>Methanol FCEV</td>
<td>Methanol fuel cell electric vehicle</td>
</tr>
<tr>
<td>CNG ICEV</td>
<td>Compressed Natural Gas-powered car</td>
</tr>
</tbody>
</table>

*Battery disposal not included  ^Pollutants include SO\(_x\), NO\(_x\), VOCs and PM

### Well-to-wheels efficiency %

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline ICEV</td>
<td>17%</td>
</tr>
<tr>
<td>Coal to BEV*</td>
<td>26%</td>
</tr>
<tr>
<td>NG to BEV*</td>
<td>28%</td>
</tr>
<tr>
<td>Methanol ICEV</td>
<td>24%</td>
</tr>
<tr>
<td>Methanol FCEV</td>
<td>29%</td>
</tr>
<tr>
<td>CNG ICEV</td>
<td>19%</td>
</tr>
</tbody>
</table>

### Cost $/km

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Cost $/km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline ICEV</td>
<td>16.4</td>
</tr>
<tr>
<td>Coal to BEV*</td>
<td>26.8</td>
</tr>
<tr>
<td>NG to BEV*</td>
<td>38.0</td>
</tr>
<tr>
<td>Methanol ICEV</td>
<td>14.5</td>
</tr>
<tr>
<td>Methanol FCEV</td>
<td>16.6</td>
</tr>
<tr>
<td>CNG ICEV</td>
<td>19.1</td>
</tr>
</tbody>
</table>

### CO\(_2\) Emitted g/km

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>CO(_2) Emitted</th>
</tr>
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<tr>
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<td>390</td>
</tr>
<tr>
<td>NG to BEV*</td>
<td>310</td>
</tr>
<tr>
<td>Methanol ICEV</td>
<td>160</td>
</tr>
<tr>
<td>Methanol FCEV</td>
<td>155</td>
</tr>
<tr>
<td>CNG ICEV</td>
<td>155</td>
</tr>
</tbody>
</table>

### Pollutants^ Emitted mg/km

<table>
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<th>Vehicle Type</th>
<th>Pollutants^ Emitted</th>
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</tbody>
</table>
Methanol Fuel is Cost-Competitive

<table>
<thead>
<tr>
<th>Resource cost</th>
<th>Conversion cost</th>
<th>Shipping cost</th>
<th>Location-specific distribution cost</th>
<th>End user cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline / Diesel</td>
<td>Refining</td>
<td>$0.30</td>
<td>$2 – 4</td>
<td>$13 – 18*</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>Liquefaction + Shipping + Regasification</td>
<td>$5 – 12</td>
<td></td>
<td>$12 – 22</td>
</tr>
<tr>
<td>Methanol</td>
<td>Methanol Production</td>
<td>$0.50</td>
<td>$4 – 7</td>
<td>$11 – 16</td>
</tr>
</tbody>
</table>

a) Distribution costs can vary widely from country to country and locations within each country
b) Corresponds approximately to crude oil price of $50 – 60 per barrel
c) Before tax on gasoline / diesel. In the US, tax is around $3.50-4.00/MMBtu

Source: Internal analysis, US data points from EIA website as at April 6, 2017
3G-Gas: Methanol Synthesis
Ultra-Low Emissions (ULE) – Natural Gas based

Efficient Economic Environment-friendly

Advanced reformer utilizes CO₂ from combustion in the synthesis

* Comparable CO₂ emissions for 1G-Coal and 2G-Gas are 3.33 and 0.56 tons respectively
Shale Gas increases Global Gas Reserves Massively

Countries with over 4.5 Trillion Cubic Meters

![Map with countries and their natural gas reserves](image)

- **Iran**: 34.0 TCM
- **Russia**: 32.3 TCM
- **China**: 31.6 TCM
- **Qatar**: 24.5 TCM
- **US**: 20.0 TCM
- **Canada**: 16.2 TCM
- **Argentina**: 15.4 TCM
- **Mexico**: 10.4 TCM
- **Brazil**: 6.9 TCM
- **South Africa**: 4.8 TCM
- **Australia**: 2.8 TCM

**Source:** BP Statistical Review 2016, USGS, U.S. EIA, Australian ERA

* Bboe = billion barrels of oil equivalent
5G Energy System Inspired by Nature

- Harvest
- Conversion to green methanol
  - CO\textsubscript{2} Capture
  - H\textsubscript{2} Generation
  - Direct CO\textsubscript{2} Reduction
    - High Selectivity
    - Low P, Low T Catalyst
  - CO\textsubscript{2} & H\textsubscript{2}O Catalytic Conversion
    - RWGS
  - Distillation
  - Membrane Separation
- Utilization
  - Recycle CO\textsubscript{2} & H\textsubscript{2}O
  - CH\textsubscript{3}OH

5G+ Artificial Photosynthesis Emulating Nature

- Hybrid Approach Integrating Synthetic Biology
- Liquid Fuels
Methanol – Liquid Electricity & Liquid Hydrogen
Storing electricity & hydrogen as liquid at ambient conditions

Methanol CH₃OH has, on a volume basis, 40% more H₂ than liquid hydrogen at -253°C, and 140% more H₂ than compressed hydrogen at 700 bars.
Methanol Applications
versatile & multi-purpose resource

- Hydrogen applications
  - Marine
  - Ground transport
  - Heat & power
  - Petro-chemicals

- Liquid Hydrogen
- Clean Fuel Oil
- Liquid Electricity
- Clean Crude

Green Methanol
Easy to store and distribute
Harnessing Sunshine
Inspired by Nature vs. Business as Usual

3E must be applied from start to end

Recap of slides 10-12, and 3E criteria - Efficiency, Economics, Environment
## Liquid Sunshine Methanol Roadmap

<table>
<thead>
<tr>
<th>Phase I</th>
<th>Phase II</th>
<th>Phase III</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fossil Methanol</strong></td>
<td><strong>Clean Methanol</strong></td>
<td><strong>Green Methanol</strong></td>
</tr>
<tr>
<td>1G-Coal</td>
<td>3G-Gas/Ule</td>
<td>4G-Biomass</td>
</tr>
</tbody>
</table>

- **First** Deployment: 2020, 2025, 2030, 2040
- **Mass** Deployment: 2050, 2070

* Commissioning of first commercial viable production facility
^ Deployment meeting over 15% of total energy consumption
Liquid Sunshine Economy
Clean Reliable Fuel for the Common Man

- Blue Sky
- Good Jobs
- Energy Diversity
- Energy Security
- Economic Growth
- Stop Climate Change
- Happy Families
- Prosperity
- Global Peace
- Stewardship of the Living Earth
Treat the earth well – it is borrowed from our children and our children's children.

collective wisdom from the early centuries to the present