Renewable Methanol: The Key to the Sustainable Fuel Puzzle

OUR BASIC MESSAGE:

Alcohol fuels-vehicle technologies may be the most cost effective GHG reduction strategies
- Higher octave fuels enable higher IC engine efficiency
  - Ethanol and methanol blends
  - Refining HC processing
- High efficiency ICE coupled with electrification provides a cost effective pathway to achieving GHG reductions
  - DI, turbocharged, downsized, down speed, high compression
- Need to minimize future fuel and vehicle costs
  - High octave gasoline an option but possibly more expensive if hydrocarbon processing used
  - Ethanol or methanol may be the best fueling options either in lower level blends or in higher level blends
  - Need also to minimize battery storage

The Renewable Methanol achieves GHG savings of 90.4%. Compared to existing alternative options this is a very positive result.
Methanol’s Key Advantages to Build On:

- The chemical simplicity of methanol is one of its important strengths:
  - Unlike gasoline, there are no carbon-carbon bonds in methanol, which translates directly into low particulate matter or soot formation potential;
- GEM blends offer an elegance direct path to market as they can be readily formulated to achieve the equivalent octane, latent heat, Btu content and air-fuel stoichiometry of E85 used in current flexible fuel vehicles (FFVs);
- Moving past low volume ethanol blends would provide a more favorable and broader mix of benefits and synergies
- Methanol have been shown to reduce polycyclic aromatic hydrocarbons (PAH) which drives diesel toxicity.

Robust Knowledge Base to Build On:

- Successive generations of methanol vehicle development have yielded key insights on how to leverage methanol’s advantages:
  - VW dedicated vehicles in 1980s
  - FFVs by many OEMs in the 1990s
    - Including Volvo’s 940 Environmental Concept Car
  - Lotus and Coogee GEM vehicle in the 2000s
  - Geely M100 production vehicles this decade!
  - Serenergy FCV Prototypes
**Methanol Vehicles:**

*Deep Roots + Exciting Horizons*

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**California Demonstrated Methanol as a Transportation Fuel in Light- and Heavy Duty Vehicles**

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**THE CALIFORNIA & U.S. NATIONAL CONTEXT**

California Methanol Programs in the 1980s-90s, was fundamentally a technical success.

- Sixty retail fuelling stations
- 17,500 M85-compatible vehicles - first large scale production of Flexible Fuel Vehicles
- Over 200 million miles of successful vehicle operating experience along with a zero-incident health & safety record

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**Geely's World 1st M100 OEM Production Vehicle Aimed at the EU Market**

*CRI Demonstration: Iceland, 2016*
LI Shufu, who is chairman of the Geely Group and Volvo stated that methanol fuel is safety, economy and environmentally friendly. Geely has been conducting research on methanol fuels since 2005, with 27 patents. Geely’s plant in Jinzhong, Shanxi Province capable of producing 250,000 methanol-fueled cars per year.

China Methanol Fuel Status

- **2009**: China adopted national standards for M85 and M100.
- **2012**: MIIT “high proportion” methanol demonstration to serve as the basis for M85 vehicle standards in Shanxi, Shandong, and Shanghai, and has expanded to other provinces and cities.
- **2014**: 7 million tons (2.3 billion gallons/8.7 billion liters) of methanol blended with gasoline, against total gasoline consumption of 2.25 million barrels per day or 34.5 billion gallons/130 billion liters.
- **160,000**: Vehicles converted to methanol fuel, mostly taxis.

China Dual-Fuel HD CI Engines

- Researchers at China’s Tianjin University have field-tested more than 70 heavy-duty compression ignition trucks in dual-fuel methanol/diesel conversion.
- Methanol displaces 30% of diesel consumption.
- Demonstrated compliance with China IV.
SERENEnergy PEM FC Vehicle: An Ideal Platform for Renewable Methanol

Israel Methanol Fuels Demonstrations

- Israel fundamentals:
  - Large gas finds in Israel
  - Strategic need to reduce oil dependence
  - Prime Minister Netanyahu established Fuel Choices Initiative.
  - Driven 900,000 kms on M15 fuels with improved power and torque.
  - Emissions of HC, CO, NOx, CO2, methanol, and formaldehyde all lower or similar to gasoline and all under EU standards

Australia Methanol Fuel Blending

- Methanol Fuels being commercialized in Australia
  - Project led by Coogee. Methanex is a partner
  - Path to energy security
  - Methanol excise tax free status for 10 years (~A38c/litre, ~$US 480/t)
  - Successful road trials and testing programs completed
  - Commercial roll out of GEM 8 planned in 2016; GEM15 & GEM56 in the future

EU Rally Racing with GEM Fuels

- Methanol Institute, Methanex and OCI NV (Natgasoline) sponsored GEM fuels in 2013-2014, and 2015 World Rally Championship.
- GEM Fuels: 37% Gasoline; 21% Ethanol; 42% Bio-Methanol
- 2013 Junior WRC and 2014 Fiesta Trophy Results:
  - 24 young drivers in 10 Rally Race events across Europe drove 16,000 km
  - Consumed 38,000 liters of GEM fuels
  - Saved 66,000 kilograms of CO2
A Closer Look at Methanol Benefits (1):

- High thermal efficiency due to the use of higher compression ratio enabled by methanol’s high octane, which can be leveraged by engine downsizing;
- Ultra-low knock limit due to its high octane and latent heat properties, further enhancing turbocharged high compression DI technology;
- Higher power and greater engine downsizing potential than gasoline technology;
- Higher torque and power response for a given engine size, due to its faster flame propagation coupled to its high octane value;
- Inherently lower NOx and PM due to its low temperature combustion properties.

A Closer Look at Methanol Benefits (2):

- Strong synergy and reinforcement of hybridization and electric drive train utilization in electric and fuel cell vehicles;
- Low incremental cost of flexible fuel technology capable of running on gasoline-ethanol-methanol (GEM) blends;
- High margins of in-use catalyst performance due to lower combustion and exhaust temperatures, in contrast to gasoline DI;
- Potential for ultra-low well-to-wheel GHG emissions from the use of renewable methanol;
- No equivalent “clean diesel” certification risk, complexity and reliance on consumer behavior to maintain system compliance
  - Avoidance of diesel engine complex selective catalytic reduction (SCR) and Lean NOx Trap (LNT) with very narrow or non-existent margins of compliance (e.g., VW worst case);

Methanol Lean Boosted Technology:
Likely Superior to Atkinson Cycle Alone

![Graph showing benefits of Methanol Lean Boosted Technology](image)

Leveraging GEM and FFV technology

- Methanol-based GEM blends offer an un-leveraged opportunity to extend the reach of the existing 14+ billion gallons of conventional ethanol, while also creating a clear market signal to OEMs and fuel providers to make long term investment in alcohol compatible infrastructure.
- Both alcohols – ethanol and methanol – offer major advantages to auto manufacturers when facing difficult emissions in-use compliance challenges associated with gasoline or diesel direct injection technology.
- The deployment of over 17 million flexible fuel vehicles in the U.S. represents the largest alternative fuel compatible fleet ever achieved, and while ethanol demand for FFVs has remained flat at just 200 million gallons per year, it is essential that this deployment be continued and leveraged fully.
GEM BLEND NOx REDUCTION POTENTIAL

50% Reduction with Methanol

GEM Blend Concentrations at 9.7:1 AFR

Straight E85 is 'dry' and has a stoichiometric AFR of 9.7:1

Blend D
Blend C
Blend B
Blend A – 'Straight' E85

- Gasoline
- The volumetric LHV is constant
- The octane numbers are constant
- The latent heat varies by ±2% across all such blends

There is therefore the potential for a true 'drop-in' solution

CRI Power - CO2 to Methanol

Renewable Methanol Plant

Chemical Reaction

Distillation

Gas Conditioning

CO2

Hydrogen

Carbon Recycling International

www.methanol.org
CRI's Renewable Methanol Production
Process Summary

Diversity of Renewable Energy Sources:
- Solar
- Wind
- Hydro
- Geothermal
- Biomass

Diversity of CO₂ Sources:
- Ethanol bio-refineries
- Ammonia plants
- Cement plants
- Steel plants
- Fossil power plants

And Recycled CO₂ Emissions
- Electricity
- Fuels

Power to Methanol:
More Efficient than Power to Methane

<table>
<thead>
<tr>
<th>SYNGAS CO₂/ft³</th>
<th>SYNGAS CO₂/ft³</th>
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<tbody>
<tr>
<td>Δ H₂O₂ [kcal/mol]</td>
<td>Δ H₂O₂ [kcal/mol]</td>
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<tr>
<td>η₁ - Δ H₂O₂ [kcal/mol]</td>
<td>η₁ - Δ H₂O₂ [kcal/mol]</td>
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| Source | Center for Solar Energy and Hydrogen Research (ZSW), Stuttgart, Germany | www.methanol.org |
Methanol Marine Fuels

- Launched in March 2015, Stena Germanica features Wärtsilä methanol-fueled marine engine in EU-sponsored effort.
- Methanex’s Waterfront Shipping 2016 delivery of seven new vessels with MAN dual-fuel methanol/diesel engines.
- MethaShip project led by Lloyd’s Register designing cruise ship and ropax ferry over next three years.
- 2016 Pilot Boat conversion by ScandiNAOS with support from MI, and Swedish Maritime Administration.
Concluding Thoughts:
No Single 2050 “Wedge” is a Guaranteed Success

The Infrastructure Costs of 100% BEV of H$_2$FCV Deployment is Much Higher Than Liquid Refueling:

<table>
<thead>
<tr>
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<th>Liquid Fuels</th>
<th>Level 3 BEV</th>
<th>Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miles of Mobility</td>
<td>119,000</td>
<td>4,800</td>
<td>4,800**</td>
</tr>
<tr>
<td>Stations to Achieve</td>
<td>1</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Energy Equivalent</td>
<td>2,000,000</td>
<td>50,000,000</td>
<td>50,000,000</td>
</tr>
<tr>
<td>Cost per station</td>
<td>150,000</td>
<td>80,000</td>
<td>2,000,000</td>
</tr>
<tr>
<td>Cost per equivalent</td>
<td>2,000,000</td>
<td>50,000,000</td>
<td>50,000,000</td>
</tr>
<tr>
<td>Network</td>
<td>$1.5 billion</td>
<td>$20 billion*</td>
<td>$500 billion</td>
</tr>
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* Assumes 100% 24 hour constant utilization of available capacity
** 80 kg per day capacity, 60 miles/kg
H2 Refueling Infrastructure Object Lesson:

• Space Shuttle External Tank H2 Capacity: 106,000 kg
• Underground H2 Tanks are not allowed
• A 10 story tank with a 27’ diameter would be needed to match liquid refueling capacity at the average station

CONCLUSIONS:

• Methanol leading to Renewable Methanol offers a “3rd Wedge” to meet CARB 2050 goals
• Optimized ICEs coupled to RM + electric drive + MIT innovations can achieve FCV-equivalence
• Liquid renewable fuels, including RM, are relevant for CA for decades
  – Integrates well with hybridization
  – Methanol-based FCVs are in use today
  – FFVs and GEM FFVs offer a key transition path
• Heavy duty and marine applications are maturing
  – Zero S, low NOx, globally mature infrastructure
• CA support for an Open Fuel Standard could revolutionize and expedite the path to sustainable alcohol fuels untethered to any land use or food market impacts

SUPPLEMENTAL SLIDES
POSITIVE OUTCOMES
+ Distillation Properties
+ Water Solubility
+ Material Compatibility in + FFVs
+ Vehicle Emission Impacts (e.g., HCHO standard adopted and easily compiled with via close coupled catalysts)
+ Octane Effects
+ Blending Vapor Pressure
+ Toxicity of Vapors
+ Risk Mitigation (e.g., flame arrestors, antisiphoning devices)

METHANOL AS A MOTOR VEHICLE FUEL
Ultra-high Efficiency Characteristics:
+ Methanol use in spark ignition engines allows higher efficiencies by increasing the engine knock limit.
+ Methanol has much higher flame speed, which allows for tighter combustion control and more precise torque management.
+ Improving knock performance is important to help avoid undesired detonation while also allowing for highly effective recovery of energy from exhaust heat.

Properties MeOH ↔ gasoline & implications

<table>
<thead>
<tr>
<th>Properties</th>
<th>Methanol</th>
<th>Gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>High heat of vaporization (Btu/lb)</td>
<td>325</td>
<td>1100</td>
</tr>
<tr>
<td>High octane number (RON)</td>
<td>95</td>
<td>109</td>
</tr>
<tr>
<td>High flame speed (Laminar burning velocity at NTP (cm/s))</td>
<td>45</td>
<td>29</td>
</tr>
</tbody>
</table>

Potential
+ Even for gasoline-optimized engine max, achievable engine load higher when using alcohols:
  - Increase in volumetric eff. due to high degree of charge cooling.
  - Spark timing less knock limited due to elevated knock resistance and higher flame speeds.
+ Options for dedicated engines:
  - High compression ratio
  - High EGR rates
  - Lean operation
Logical Progression for Future Methanol Optimization:

- Super-efficient Spark Ignition Methanol Engines (Similar efficiency to fuel cell propulsion)

ATMOSPHERIC DECARBONIZATION

E.G., Palo Alto Research Center et al.

Converted VW Turbo-Diesel to Methanol PFI Spark-ignition

Gasoline-Ethanol-Methanol (GEM) Blends Potential Efficiency

GEM blends have same air fuel ratio as E85

- Provide opportunity to extend reach of ethanol by blending with methanol for FFV use
- All GEM blends have consistently higher octane levels than gasoline
- GEM Fuel “Elegance”

GEM blends have same:
- air fuel ratio
- gravimetric & volumetric heating values
- octane
- heat of vaporization
- O2 sensor output as E85

Compatible with E85 calibrated FFVs from a combustion standpoint
Methanol Air Quality & GHG Benefits
Inherently lower NOx and PM due to low temperature combustion properties;
C1 compounds in M85 compared to the much higher carbon content of reformulated gasoline.

A lack of carbon-carbon bonds results in ultra-low particulate emissions.
The atmospheric reactivity of methanol is recognized to have lower ozone forming potential compared to the olefins and aromatics present in gasoline.

Methanol & Fuel Cells
- Methanol is used in fuel cell applications as a high density source of hydrogen for PEM fuel cells, and in direct methanol fuel cells.
- Methanol-based fuel cell vehicles are in current demonstration in Denmark by Serenex.
- Argonne National Lab found methanol fuel cells coupled to hybridized electric drivetrains would have significantly lower GHG emissions compared to fuel cell vehicles using hydrogen derived via electrolysis using natural gas.

Methanol Marine Fuels
Launched in March 2015, Stena Germanica features Wärtsilä methanol-fueled marine engine in EU-sponsored effort.

Recent testing by Stena demonstrated NOx emissions can be decreased by up to 70% while achieving parity with diesel cycle marine engines.

Reduced NOx (~70%)  Some efficiency as diesel

Enerkem – Waste to Methanol
Will bring Edmonton's recycling rate from 60% to 90%

World's first commercial MSW-to-biofuels and chemicals facility.

ENERKEM ALBERTA BIOFUELS
Capacity: 36 million litres per year
Feedstock: 25-year agreement with City of Edmonton to 3,000,000 dry tonnes M3W per year
Products: Biomethanol, cellulose ethanol

5/11/2016
Methanol Deployment in Light Duty Vehicles

Recent work for Fuel Freedom Foundation has shown methanol can be a viable alternative to meet goals of petroleum displacement and lower emissions of greenhouse gases (GHG), criteria, and toxic emissions.

- Substantial increase in U.S. Natural Gas Supply due to shale exploration and production
- Gasoline, Ethanol, Methanol (GEM) Blends have been demonstrated in existing ethanol FFVs
- Meeting Climate Change objectives will require large GHG emissions reductions


Methanol Deployment in Light Duty Vehicles

California Methanol Program Legacy

- CAFE incentives developed for alternative fuel vehicles
- First for methanol and then for ethanol flexible fuel vehicles (FFVs)
- U.S. FFV population around 20 million vehicles
- Low incremental vehicle costs easy for OEMs to produce
- Most gasoline soled in U.S. is E10 at 87 octane (r+ml2)
- 10% ethanol blended in reformulated blend for oxygen blends
- Reformulated E10 reduces air pollution
- Small but growing E85 infrastructure
- Little E85 used due to unfavorable pump pricing
- ASTM D5798-13a defines E85: 51-83% ethanol

Methanol Fuels used in Fuel Flexible Vehicles (FFVs) and converted gasoline FFVs could provide a cheaper fuel at the pump

- GEM fuels transparent to FFVs with possible exception of material compatibility with methanol blends and evaporative emissions at low blend levels (M10)
- GEM fuels may also operated in modern gasoline technology vehicles—some conversion software and/or hardware may be needed
Methanol Deployment in Light Duty Vehicles

Outlook

Methanol has the potential to compete in the LDV market

- Price competitive at the pump
  - Need consumer value proposition
- Market methanol to existing and converted FFVs to establish fuel demand
  - Solve any material and evaporative emission issues
  - ASTM 5797-13 defines methanol as M51-M85
- Introduce dedicated high efficiency ICEs using methanol
  - High compression, DI, Turbocharged, downsized and downspeed
  - Take advantage of methanol fuel properties
- Integrate high efficiency ICE with electric vehicle platforms
  - Hybrid electric vehicles
  - Plug-in hybrid electric vehicles