CAL POLY RENEWABLE FUEL INITIATIVE

Business-Technology Roadmap

Methanol, Dimethyl Ether, and Ammonia

First Edition

November 30, 2012

CLINTON FOUNDATION
CLINTON CLIMATE INITIATIVE

Introduction

Dr. William Ahlgren, Associate Professor of Electrical Engineering at California Polytechnic State University, submitted a proposal for a Renewable Fuels Initiative to the California Energy Commission on August 2, 2012. The mission of the Initiative would be to create an energy transition roadmap and facilitate its implementation. The animating idea of the roadmap would be to replace fossil with renewable and perhaps nuclear energy sources. It would involve building an energy system based on three energy carriers: electric power and two liquid renewable fuels, one nitrogen-based, e.g. ammonia, and one carbon-based, e.g. methanol. The transition would require coordinated technology and business development plans. To meet this need, the Initiative would promote both technological and institutional innovation.

The Clinton Climate Initiative (CCI) concurs with Dr. Ahlgren about the need for an Initiative of the type proposed and on its choice of target energy carriers. CCI's Transportation Program has agreed to apply its expertise in the policy and business dimensions of advanced transportation technologies on behalf of the Initiative. As a first step, CCI has convened two panels of experts to support the drafting of a "First Edition Business -Technology Roadmap" for near-term commercialization of three fuel species that are of primary interest to the Initiative. This document is the result of that effort.

Scope of the Roadmap

- The Roadmap describes how three fuel species – methanol, dimethyl ether (DME), and ammonia – will get from the status quo to full commercialization
- Status quo = little/no presence in transportation fuel markets
- Full commercialization = "chickens and eggs" =
  - Price-competitive availability of vehicles that run on the given fuel species
  - Cost-competitive production and distribution of the fuel
  - Availability of the fuel at appropriate dispensing locations
- U.S.-centric with reference as appropriate to other countries
- Focused on on-road applications but off-road, rail, and marine applications could also come into play

CLINTON FOUNDATION | CLINTON CLIMATE INITIATIVE

This Document . . .

- Is the first edition of the Business-Technology Roadmap that will inform the agenda of the proposed Renewable Fuels Initiative
- Contains material that is indicative rather than definitive; it can and will be refined in parallel with the development of the concept for the Initiative
- Refers to the benefits and advantages of the three species addressed but does not attempt to present the full, integrated case for them

Theme: These Fuels Are Ready Now

- The technologies associated with methanol, DME, and ammonia exist today – on both the fuel production and vehicle application sides
- In each case full-scale industrial facilities are already producing one or more "green" versions of the fuels or will shortly enter the construction phase
- In each case, there is a rational path for gaining first a foothold and then a growing position in the transportation fuel market
- In each case, one or more internal combustion engines designed for the fuels has at least reached the demonstration stage
- In each case, there is a history of industrial production and use of the species that contains answers to many questions that will be asked about their potential use as transportation fuels

Methanol/DME Advisory Group

Member	Title	Organization
Dan Cohn	Senior Research Scientist, Head, Plasma Technology Division	Massachusetts Institute of Technology
Greg Dolan	Acting CEO	Methanol Institute
John Bøgild Hansen	Senior Scientist, Advisor to Chairman	Haldor Topsoe A/S
Ben Iosefa	Director, Strategic Marketing Planning	Methanex Corporation
Paul Wuebben	Senior Director for Renewable Fuels	Carbon Recycling International

Ammonia Fuel Advisory Group

Member	Title	Organization
Bill Ayres	New Projects Manager	R3 Sciences, LLC
Dave Drury	Director of Advanced Development	Sturman Industries
James Grieve	Chief Scientist	Delphi Corporation
John Bøgild Hansen	Senior Scientist, Advisor to Chairman	Haldor Topsoe A/S
John Holbrook	Chief Executive Officer	NHThree, LLC
Jeff Newman	Staff	California Business, Transportation, and Housing Agency
Norm Olson	Biomass Energy Conversion Center Facility Manager	Iowa Energy Center
Jeff White		Denso International America

Methanol

Methanol Pathways of Interest

- Methanol fuel commercialization can proceed along three pathways:
  1. Neat fuel for medium- and heavy-duty engines
     - Dual-fuel engines are under development with support from the USEPA
  2. High-concentration methanol-gasoline blends for light-duty FFVs
     - >50% methanol blends in FFVs optimized for methanol's special properties (e.g., higher octane and latent heat of vaporization which could enable higher BTU efficiency)
     - Methanol-ethanol-gasoline (GEM) ternary blends in existing ethanol E-85 FFVs
     - Longer-term integration of PHEV and FFV technology
  3. Low-level blends for the existing fleet of light-duty vehicles

An Illustrative Approach

- The steps proposed on the following slides represent one possible approach to navigating the potential pathways for methanol
- The steps focus initially on neat methanol for heavy-duty applications and subsequently on high-concentration methanol-gasoline blends for light-duty applications
- In practical reality, adjustments to any chosen approach can and should be made in light of accruing developments on relevant fronts of technology, business, and regulation

Steps to MeOH Commercialization

Step MF1
Initiate production of renewable methanol (RM)
2011

Step MF2
Gain ARB recognition for renewable methanol as a Low-Carbon Fuel
2014

Step MF3
"Normalize" methanol's status as a transportation fuel in CA
2016

Step MF4
Establish methanol distribution points in selected metropolitan areas
2016 →

Step MF5
Introduce high-concentration gasoline blends for use in FFVs
2020

Step MV1
Demonstrate current-generation methanol engine technology
2013

Step MV2
Gain ARB certification for methanol engine
2016

Step MV3
Offer methanol engine for commercial sale
2016

Step MV4
Penetrate truck fleets that operate within metropolitan areas
2016 →

Step MV5
Introduce M85-rated FFVs
2020

Step MF1

Step MF1

Initiate production of renewable methanol

- Feedstock: Recycled CO_2 and/or waste biomass
- Market: European Union
- Effect: RM is available for jurisdictions in which there is demand for it

Players and Actions

- Carbon Recycling International opened its first full-scale electrochemical methanol production plant in September 2011
- Companies such as Sundrop Fuels and Syngest are working on full-scale biomass conversion plants the designs of which could be adapted to produce RM
- Companies such as BioMCN and Enerkem are producing RM from other renewable feedstocks

Note

There is no discrete step for the production of conventional methanol because it is widely manufactured at high volume and is universally distributed.

Note

Preliminary modeling indicates that renewable methanol can be produced at a cost that is competitive with corn-based ethanol and even with gasoline at current oil prices

Source: CCI modeling of biomass gasification processes

Step MV1

Step MV1
Demonstrate current-generation methanol engine technology
- Vehicles: Heavy-duty
- Fuel: Conventionally produced methanol

Players and Actions
- Cooperation is needed between a vehicle OEM and a fleet proprietor

Note
The USEPA is working with a major heavy-duty engine producer and a major delivery company toward commercialization of a dual –fuel, diesel-methanol, compression-ignition platform. The approach allows for upfitting of production engines and vehicles rather than developing a full suite of components from scratch.
Source: "Efficient Use of Natural Gas Based Fuels in Heavy-Duty Engines", National Center for Advanced Technology, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. October 2012

Step MF2

Step MF1
Initiate production of renewable methanol

Step MF2
Gain ARB recognition for renewable methanol as a Low-Carbon Fuel

- Effect: Methanol will gain entrée to the category of "go-to" fuels of the future

Players and Actions

- Renewable methanol producers have a natural motivation to secure recognition

Note
Renewable methanol can be produced via several methods. Electrochemical reduction of CO_2 and the gasification of waste biomass are two that hold the potential for very low GHG footprints. Like production of dairy digester biogas (13 gCO_2e/MJ), both employ only waste feedstocks and neither involves significant use of fossil-derived energy at any stage of the production and use lifecycle.

Step MV2

Step MV1
Demonstrate current-generation methanol engine technology

Step MV2
Gain ARB certification for one or more heavy-duty methanol engines
- Effect: Sales can be started in mainstream transportation markets

Players and Actions
- Methanol engine producers have a natural motivation to secure certification

Note
Internal combustion of methanol (in a high-concentration gasoline blend, neat, or with dual-fuel engine technology) does not pose an unfamiliar or significant challenge with regard to emissions compliance. The dual-fuel platform, for example, promises compliance via the use of exhaust gas recirculation, diesel particulate filtration, and a direct oxidation catalyst.
Source: "Efficient Use of Natural Gas Based Fuels in Heavy-Duty Engines", National Center for Advanced Technology, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. October 2012

Step MF3

Step MF2
Gain ARB recognition for renewable methanol as a Low-Carbon Fuel

Step MF3
"Normalize" methanol's status as a transportation fuel in California

- Confirm existing ARB approval of high-concentration blends as "alternative fuel" for methanol-certified engines in heavy-duty applications
- Gain ARB approval for low-concentration gasoline blends

Players and Actions

- Conventional and renewable methanol producers have a natural motivation to secure approval

Note
Methanol has a long history and current status as a transportation fuel. It is a permitted constituent of European gasoline in concentrations up to 3% under EU Norm EN228. The USEPA has a history of favorable action on low-concentration methanol-gasoline blends, including the recent waiver grant for a corrosion-inhibiting gasoline formulation that would involve 5% methanol.
Sources: EU, "EU Biofuels Platform", http://www.biofuels-platform.ch/en/home/; USEPA, "EPA Announces Decision for Regulation of Fuel and Fuel Additives: Modification to Octamix Waiver Regarding TOLADMFA-10A", June 2012

Step MV3

Step MV2
Gain ARB certification for methanol engine

Step MV3
Offer methanol engine for commercial sale
- GVWR coverage: Classes 6 and 8 via the EPA's dual-fuel engine program
- Effect: Fleet proprietors can convert to methanol

Players and Actions
- To justify the investment in marketing and sales, vehicle OEMs must identify a driver for market uptake for methanol-powered trucks

Note
The EPA's economic modeling shows the potential for a substantial lifecycle cost advantage for a methanol dual-fuel engine vs. 2010 diesel technology based on savings in up-front vehicle price, increased engine efficiency , emissions control, and fuel price.
Source: "Efficient Use of Natural Gas Based Fuels in Heavy-Duty Engines", National Center for Advanced Technology, Office of Transportation and Air Quality, U.S. Environmental Protection Agency. October 2012

Step MF4

Step MF3
Gain ARB approval for methanol as a transportation fuel

Step MF4
Establish methanol distribution points in selected metropolitan areas

- Model: Roll out of CNG fueling facilities in cities around the world, typically involving an initial mix of private-dedicated, private-with-public-access, and wholly public installations

Players and Actions

- Fuel suppliers must identify situations (customers, venues, and partners both private- and public-sector), that will support a positive return on the investment in facilities

Step MV4

Step MF4
Establish methanol distribution points in selected metropolitan areas

Step MV4
Penetrate truck fleets that operate within selected metropolitan areas
- Selling points: Reduce operating costs, increase sustainability, increase energy independence
- Effect: Creation of enough demand (and visibility) for methanol fuel to make the case for its application to light-duty vehicle applications

Players and Actions
- Vehicle OEMs must undertake sales and marketing campaigns
- Public-sector agencies can serve as pioneering customers

Note
"Intra-city" trucks (as distinct from those that operate on an inter-city basis) account for approximately one-third (15 billion gallons) of U.S. diesel fuel consumption in the on-road transportation sector.
Source: Energy Information Administration, using "single unit trucks" as a proxy for "intra-city" trucks

Step MV5

Step MV4
Penetrate truck fleets that operate within metropolitan areas

Step MV5
Introduce M85-rated FFVs
- Effect: Opening of the light-duty vehicle market to methanol fuel

Players and Actions
Automotive OEMs need to embrace and promote the idea of an even more flexible FFV

Note
The incremental cost for a methanol-ready car is the same as for an ethanol-ready car (~$100 in both cases)
Source: Methanol Institute, http://www.methanol.org/Energy/Transportation-Fuel.aspx

Note
Methanol has several characteristics as an internal combustion fuel that permit engine efficiency as much as 30% higher than that of gasoline. Even conventionally produced methanol, therefore, could help OEMs meet their Corporate Average Fuel Efficiency (CAFÉ) obligations.
Source: Remarks by Dan Cohn, Senior Research Scientist, Head, Plasma Technology Division, Massachusetts Institute of Technology

Step MF5

Step MV5
Introduce M85-rated FFVs

Step MF5
Introduce high-concentration gasoline blends for use in flex-fuel vehicles (FFVs)

- Target blend range: 56-85% methanol
- Effect: Opening of an opportunity for deep displacement of petroleum-based fuels

Players and Actions
Automotive OEMs need to embrace and promote the idea of an even more flexible FFV

Note
With today's prices for conventional methanol, M85 would retail at about the same price per gasoline-gallon-equivalent as gasoline
Source: CCI analysis based on "Methanol Fuel Blending Characterization and Materials Compatibility", TIAX, 8/10

Note
M56 is identical to E85 in key characteristics including volumetric energy content, octane number, and latent heat[1]. M85 is currently seen as the maximum concentration that contains enough gasoline for goo d cold-start performance.
1. Source: Lotus Engineering, "Evolution Of Alcohol Fuel Blends Towards a Sustainable Transport Energy Economy", 2012 MITEI Symposium

CLINTON FOUNDATION | CLINTON CLIMATE INITIATIVE

Additional Pathways

- The steps detailed above do not address the opportunities for low-concentration RM-gasoline blends or high-concentration “alcohol” blends involving both methanol and ethanol
- The approach on these fronts is distinct from that of the other two pathways but the impact could be significant
- For example, low-concentration blends involving renewable methanol (e.g., RM5) could make an important contribution to the Federal target for renewable fuel usage
  - Five percent of the U.S. gasoline pool in 2011 represented a volume of 7 billion gallons[1]; this is almost 20 percent of the total requirement for renewable fuel under the Federal Advanced Renewable Fuel Standard in 2022
- Following are summaries for pathways that could address these opportunities

1. Source: Energy Information Administration

Alternative "Alcohol" Pathway

Step MF1.A
Identify regulatory and market barriers to ternary GEM (gasoline-ethanol-methanol) blends

→

Step MF2.A
Perform required testing and gain regulatory approvals

→

Step MF3.A
Commercial roll-out of GEM blends

Step MV1.A
Perform vehicle fleet demonstrations of GEM blends in E85 FFVs

→

Step MV2.A
Gain automotive OEM support for the addition of a new type of light-duty fuel

→

Step MV3.A
Commercial roll-out of GEM-rated vehicles

Alternative Low-Level Blend Pathway

Step MF1.B
Identify regulatory and market barriers to low-concentration RM fuel blending

→

Step MF2.B
Perform required testing and gain regulatory approvals

→

Step MF3.B
Commercial roll-out of RM5

Step MV1.B
Perform vehicle fleet demonstrations of low-concentration methanol-gasoline blends in conventional light-duty vehicles

→

Step MV2.B
Gain automotive OEM support for the addition of a new type of light-duty fuel

→

Step MV3.B
Commercial roll-out of RM5-rated vehicles

Dimethyl Ether

DME Pathway

- DME may be on a faster track than methanol or ammonia
  - Two companies have engines that are already well into multi-year demonstration programs
  - At least one company is well along in establishing a fueling arrangement – including a dedicated fuel production facility – for a closed-loop truck fleet
  - There is reason to hope that regulatory acceptance of the fuel is possible in the relative near-term
- The pathway described on the following slides is premised on the continuation of current momentum

Steps to DME Commercialization

Step DF1
Set up site(s) for the initial use of DME as a transportation fuel

2013

→

Step DF2
Gain ARB approval for DME as a transportation fuel

2014

→

Step DF3
Initiate distributed production of DME

2015

→

Step DF4
Initiate production of renewable DME

2015

→

Step DF5
Establish fuel distribution points for DME in selected metropolitan areas

2016 →

↓

Step DV1
Gain ARB certification for DME engine

2014

→

Step DV2
Offer DME engine for commercial sale

2015

→

Step DV3
Penetrate truck fleets that operate within metropolitan areas

2016 →

Step DF1

Step DF1

Set up site(s) for the initial use of DME as a transportation fuel

- Customers: "Closed loop" truck fleets that return to a home base every night
- Effect: Technical viability of the fuel is demonstrated

Players and Actions

- Companies such as Oberon Fuels and GV Energy are working to launch pilot facilities

Steps DF2

Step DF1
Set up site(s) for the initial use of DME as a transportation fuel

Step DF2
Gain ARB approval for DME as a transportation fuel

- Effect: DME is cleared for use as a transportation fuel in the State of California and other CARB states

Players and Actions

- Oberon Fuels is serving as the fuel's champion in the initial stages of ARB's review

Step DV1

Step DF1

Set up site(s) for the initial use of DME as a transportation fuel

Step DV1

Gain ARB certification for DME engine

- Effect: DME engines are cleared for sale in the State of California and other CARB states

Players and Actions

- OEMs will marshal their engines through the certification process

Note

Volvo's DME EUV engine has accumulated more than 700,000 km in Swedish field tests over the last two years. Isuzu has conducted road tests for two different DME engines over the last three years, also with the accumulation of several hundred thousand km of experience.

Source: BioDME "Update on Mileage of BioDME Trucks", 10/5/12; Isuzu "Development Status of DME Vehicle in Japan" 11/16/11

Step DF3

Step DF2
Gain ARB approval for DME as a transportation fuel

Step DF3
Initiate distributed production of DME

- Feedstock: Methane (natural gas and/or renewable gas)
- Effect: Creates a practical and potentially bankable approach for incremental development of fueling infrastructure

Players and Actions

- Fuel suppliers will deploy small-scale production assets at or near customer truck depots

Note
At least two fuel suppliers are working with process engineering firms to develop plants that can be fed off natural gas distribution lines and located at or near points of dispensing.
Source: Confidential supplier discussions with CCI

Step DV2

Step DV1
Gain ARB certification for DME engine

Step DV2
Offer DME engine for commercial sale

- GVWR coverage: Classes 5, 6, 7, and 8 via 5.2 liter (Isuzu), 12.8 liter (Volvo) engines
- Effect: Fleet proprietors can convert to DME

Players and Actions

- To justify the investment in marketing and sales, engine OEMs must identify a driver for market uptake for DME-powered trucks

Note
DME engines have the potential for reduced operating costs vs. current clean-diesel technology. Volvo's DME engine meets the Euro 5 emissions standard using a direct oxidation catalyst (DOC) to control CO and HC and exhaust gas recirculation (EGR) for NOx. Neither particulate filters nor selective catalytic reduction (SCR) are required. Fuel efficiency is equal to that of diesel on an energy-equivalent basis.
Source: Volvo, "BioDME: From Wood to Wheel", 11/16/11

Step DF4

Step DF3
Initiate distributed production of DME

Step DF4
Initiate production and distribution of renewable DME

- Feedstock: Black liquor from paper industry or waste biomass
  Method: Gasification (could be in conjunction with methanol production)
- Effect: DME becomes a "cellulosic biofuel" ready for acceptance under renewable fuel standards (RFS) in the U.S. and Europe and thereby can test its cost-competitiveness with other renewable fuels within that arena

Players and Actions

- Fuel producers such as Chemrec must establish feedstock sourcing arrangements, production facilities, and distribution methods

Note
Chemrec is building an industrial-scale demonstration of black liquor gasification in Sweden. Approval was received in 2011 for an investment grant of up to $73 million from the Swedish Energy R&D Board.
Source: Chemrec

Step DF5

Step DF4
Initiate production and distribution of renewable DME

Step DF5
Establish fuel distribution points for DME in selected metropolitan areas

- Model: Roll out of CNG fueling facilities in cities around the world, typically involving an initial mix of private-dedicated, private-with-public-access, and wholly public installations

Players and Actions

- Fuel suppliers must identify situations (customers, venues, and partners both private- and public-sector), that will support a positive return on the investment in facilities

Step DV3

Step DF5
Establish fuel distribution points for DME in selected metropolitan areas

Step DV3
Penetrate truck fleets that operate within selected metropolitan areas

- Selling points: Reduce operating costs, reduce criteria emissions, reduce greenhouse gas emissions, increase energy independence

Players and Actions

- Fuel suppliers must undertake sales and marketing campaigns
- Public-sector agencies can serve as pioneering customers

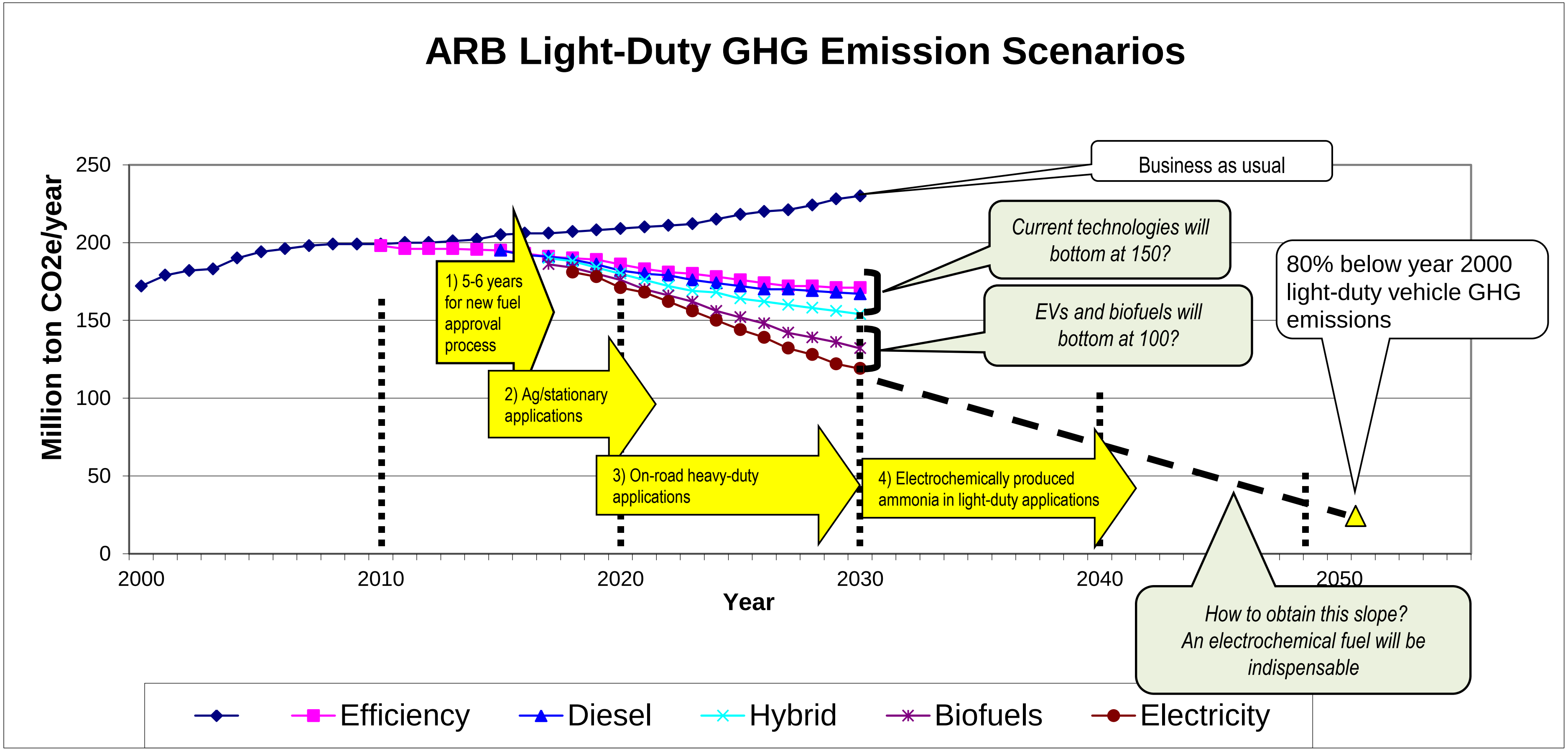
Note
"Intra-city" trucks (as distinct from those that operate on an inter-city basis) account for approximately one-third (15 billion gallons) of diesel fuel consumption in the on-road transportation sector.
Source: Energy Information Administration, using "single unit trucks" as a proxy for "intra-city" trucks

Ammonia

Ammonia Pathway

- Ammonia has not started the regulatory review process that will lead to its approval as a transportation fuel
- The proposed pathway is premised on 3-4 phases
    1. Regulatory fuel review and approval
    2. Commercialization of stationary applications
    3. Commercialization of heavy-duty on-road applications
    4. Possible penetration of light-duty on-road applications
- The first three phases are likely to play out over the next 15-20 years

Long-Term Ammonia Timeline



Steps to Ammonia Commercialization

Step AV1
Engine development phase two: vehicle demonstration and emissions profiling

2013

Step AV2
Gain stationary source certification and start sales for stationary applications

2015

Step AV3
Engine development phase three: commercial-caliber ammonia engine

2018

Step AV4
Gain mobile source certification for one or more engines

2019

Step AV5
Initiate sales to closed loop truck fleets

2020

Step AF1
Bring green ammonia plant on line

2015

Step AF2
Gain ARB approval for ammonia as a transportation fuel

2018

Step AF3
Make ammonia fuel available on a private depot basis

Step AV1

Step AV1

Engine development phase two

- Goal: Deploy an ammonia engine in a conventional vehicular application (e.g., a class 5-8 delivery vehicle) AND profile the engine's emissions
- Effect: A case can be started for the approval of ammonia fuel by regulatory authorities

Players and Actions

- Engine technology companies such as Sturman Industries, Eliminator Products, and Hydrogen Engine Center have developed all necessary components and systems and are prepared to deploy them in a phase two project

Note

Engine development phase one has already been completed with the demonstration of a vehicle fueled with pure anhydrous ammonia by Eliminator Products.

Step AF1

Step AV1
Engine development phase two: vehicle demonstration and emissions profiling

Step AF1
Bring green ammonia plant on-line
- Likeliest process: Biomass gasification
- Primary initial market: Fertilizer
- Effect: Renewable ammonia will be available when vehicles are ready to use it

Players and Actions
- Companies such as Syngest are working to establish first-generation biomass-to-ammonia production facilities

Note
Ammonia can be beneficially co-produced with methanol and DME in a biomass-to-fuel plant.

Step AV2

Step AV1
Engine development phase two: vehicle demonstration and emissions profiling

Step AV2
Gain stationary source engine certification
- Effect: Sales can be started in early-adopter markets (e.g. agriculture, military)

Players and Actions
- Specialist engine technology companies will work through the certification process

Note
Hydrogen Engine Center has tested an ammonia-propane dual-fuel engine in an irrigation pumping application.

Step AV3

Step AV2
Gain stationary source certification

Step AV3
Engine development phase three

- Goals:
    1. Achieve compliance with emissions standards
    2. Achieve cost-competitiveness
    3. Achieve durability benchmarks
- In parallel: Choose on-board fuel storage and delivery system
- Effect: Availability of a "plug and play" ammonia-fuel propulsion system

Players and Actions

- Specialist engine technology companies will likely develop cooperative relationships with larger players in the global engine ecosystem

Note
Natural-gas engine technology companies such as Westport Innovations and Emissions Solutions, Inc. show how cooperative relationships can be forged between large and small engine producers.

Step AF2

Step AF1
Construct green NH3 plant

Step AF2
Gain ARB approval for ammonia as a transportation fuel
- Key requirements: emissions compliance, multi-media analysis, safety standards
- Effect: A necessary condition will be met to launch an ammonia fuel market

Players and Actions
- Ammonia producers and distributors have the strongest motivation to secure approval
- Initial leadership may come from the research and/or NGO communities

Note
The multi-media analysis may be expedited by ammonia's status as a widely used agricultural chemical. Ammonia's safety as a transportation fuel has been studied and found not to pose undue challenges.
Sources: Quest Consultants, "Comparative Quantitative Risk Analysis of Motor Gasoline, LPG, and Anhydrous Ammonia as an Automotive Fuel", June 17, 2009; Risø National Laboratory, "Safety Assessment of Ammonia as a Transport Fuel", Denmark

Step AV4

Step AV3
Engine development phase three: commercial-caliber ammonia engine

Step AV4
Gain mobile source certification for one or more engines
- Effect: Sales can be started in mainstream transportation markets

Players and Actions
- Participants in phase-three engine development will work through the certification process

Note
Early emissions profiling work indicates that exhaust aftertreatment may be required to address NOx and unburned ammonia. These two species combine to form atmospheric (diatomic) nitrogen in the reaction that is at the heart of selective catalytic reduction (SCR) technology.
Source: Gross and Kong, "Performance characteristics of a compression-ignition engine using direct-injection ammonia–DME mixtures", Fuel, 2012

Step AV5

Step AV4
Gain mobile source certification for one or more engines

Step AV5
Initiate sales to closed loop truck fleets

- Target market: Fleets that have opted out of diesel fuel (or would like to)
- Effect: Will allow the start of high-volume engine production

Players and Actions

- Truck OEMs will lead the development of this market

Note
Sturman Industries' Air Controlled Engine technology promises an unprecedented degree of flexibility in fuel selection, while retaining optimal efficiency and power. The engine can adapt in real time to the use of different fuels while meeting a goal of reducing or eliminating the formation of NOx and the associated need for SCR or other after-treatment. This opens the possibility of a truck that can accept propane, DME, and ammonia (all three of which have similar physical and handling characteristics).
Source: Sturman Industries

Step AF3

Step AF2
Gain ARB approval for ammonia as a transportation fuel

Step AF3
Make ammonia fuel available on a private depot basis

- Effect: Will strengthen demand for green ammonia

Players and Actions

- Ammonia distributors such as Airgas are considering the opportunity represented by turnkey vehicle-fuel solutions for fleet proprietors