Methanol: A Future-Proof Fuel

A Primer Prepared for the Methanol Institute

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Table of Contents

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Tammy Klein provides market and policy intelligence with unique insight and analysis drawn from her global network in the fuels industry through the consulting services she provides and the membership-based Future Fuels Outlook service. She is an expert on conventional, biofuels and alternative fuels market and policy issues. Tammy serves clients in the auto, oil and associated industries, as well as governments and NGOs and helps them understand current and future fuels trends and issues; or in the case of government and NGOs, the best policies to develop and implement. To learn more, visit her website at https://futurefuelstrategies.com/.

Introduction & Summary

Key Points in This Section:

- Methanol can be made from a wide array of feedstocks, making it one of the most flexible chemical commodities and energy sources available today.
- Methanol has the distinct advantage of "polygeneration" – as methanol can be made from any resource that can be converted into synthesis gas.
- Polygeneration, the ability to scale efficiently and cost-effectively, versatility in so many products and applications including transportation fuels, its biodegradability and its 100-year history of safe production, use and handling is what makes methanol future-proof. These attributes are especially critical in a world that is beginning to act more aggressively to reduce GHG emissions to combat climate change.
- Energy-related applications for methanol are the fastest growing segments of methanol demand and now represent 40% of global methanol consumption.
- Methanol is the world's most commonly shipped chemical commodity and is one of the top five most widely traded chemicals in the world. It has been stored, transported and handled safely for over 100 years.

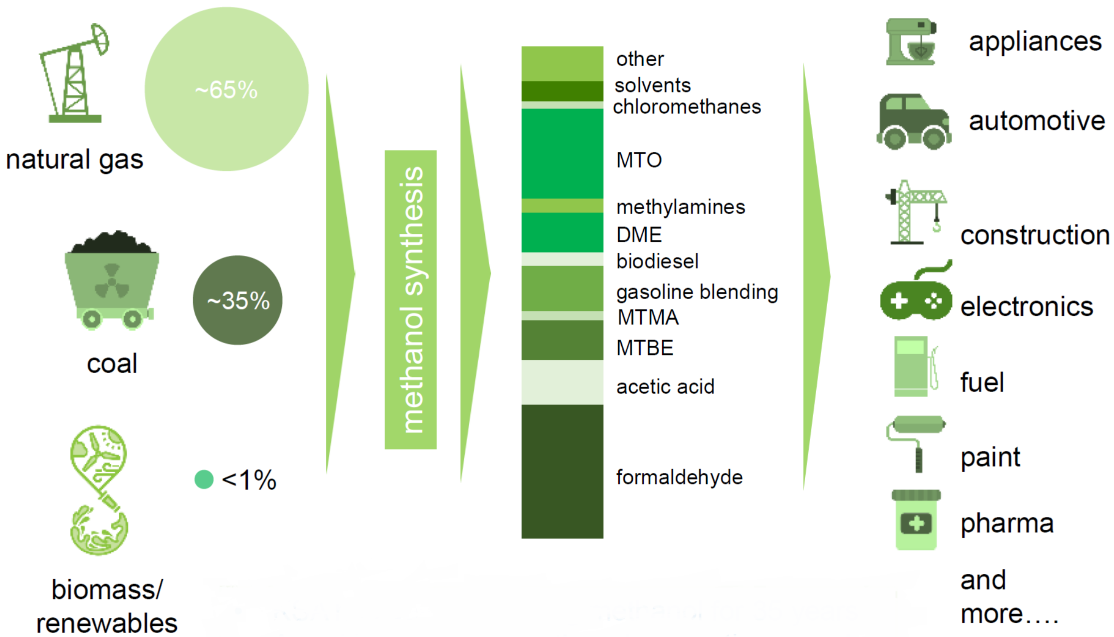
Methanol is a clear liquid chemical that is water soluble and readily biodegradable.[1] Methanol is comprised of four parts hydrogen, one-part oxygen and one-part carbon, and is the simplest member of a group of organic chemicals called alcohols. Today, methanol is predominantly produced on an industrial scale using natural gas as the principal feedstock.

Methanol is used to produce other chemical derivatives, which in turn are used to produce thousands of products that touch our daily lives, such as building materials, foams, resins, plastics, paints, polyester and a variety of health and pharmaceutical products. Methanol also is a clean-burning, biodegradable fuel. Increasingly, methanol's environmental and economic advantages are making it an attractive alternative fuel for powering vehicles and ships, cooking food and heating industry. Methanol can be made from a wide array of feedstocks, making it one of the most flexible chemical commodities and energy sources available today.

To make methanol, you first need to create synthesis gas, which is a mixture of CO, CO2 and hydrogen gas. While natural gas is most often used in the global economy, methanol has the distinct advantage of "polygeneration" as methanol can be made from any resource that can be converted into synthesis gas. Using mature gasification technologies, synthesis gas can be produced from anything that is or ever was a plant. This includes biomass, agricultural and timber waste, municipal solid waste, and several other feedstocks. Figure 1 shows methanol feedstocks, products and uses.

[1] Methanol Institute, *What Is Methanol?*, last accessed Aug. 26, 2019 at https://www.methanol.org/about-methanol/.

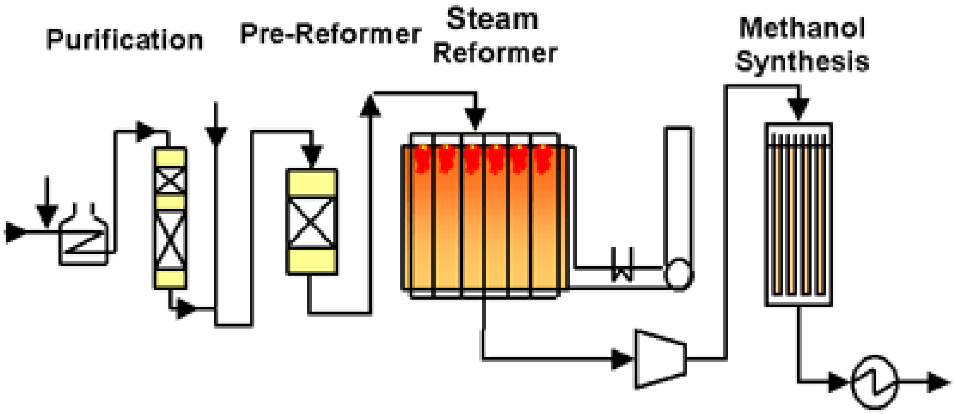
Figure 1: Methanol Feedstocks, Products and Uses



Source: Methanol Institute, April 2019

Figure 2 shows a schematic of the methanol production process.

Figure 2: Basic Methanol Production Process



Source: Methanol Institute

Synthesis gas can also be produced by combining waste CO2 from manufacturing or power plants with hydrogen produced from the electrolysis of water using renewable electricity to produce electrofuels. And just on the horizon is technology to directly capture CO2 from the atmosphere. Methanol can be manufactured from small-scale units producing a few hundred gallons or liters per day, to world-scale, “mega methanol” plants making 5000 metric tons (1.6 million gallons) each day. There are currently 90 world-scale methanol plants capable of producing 110 million metric tons (36.6 billion gallons) of methanol annually. Anywhere in the world, there is feedstock and production technology that can be used to make methanol.

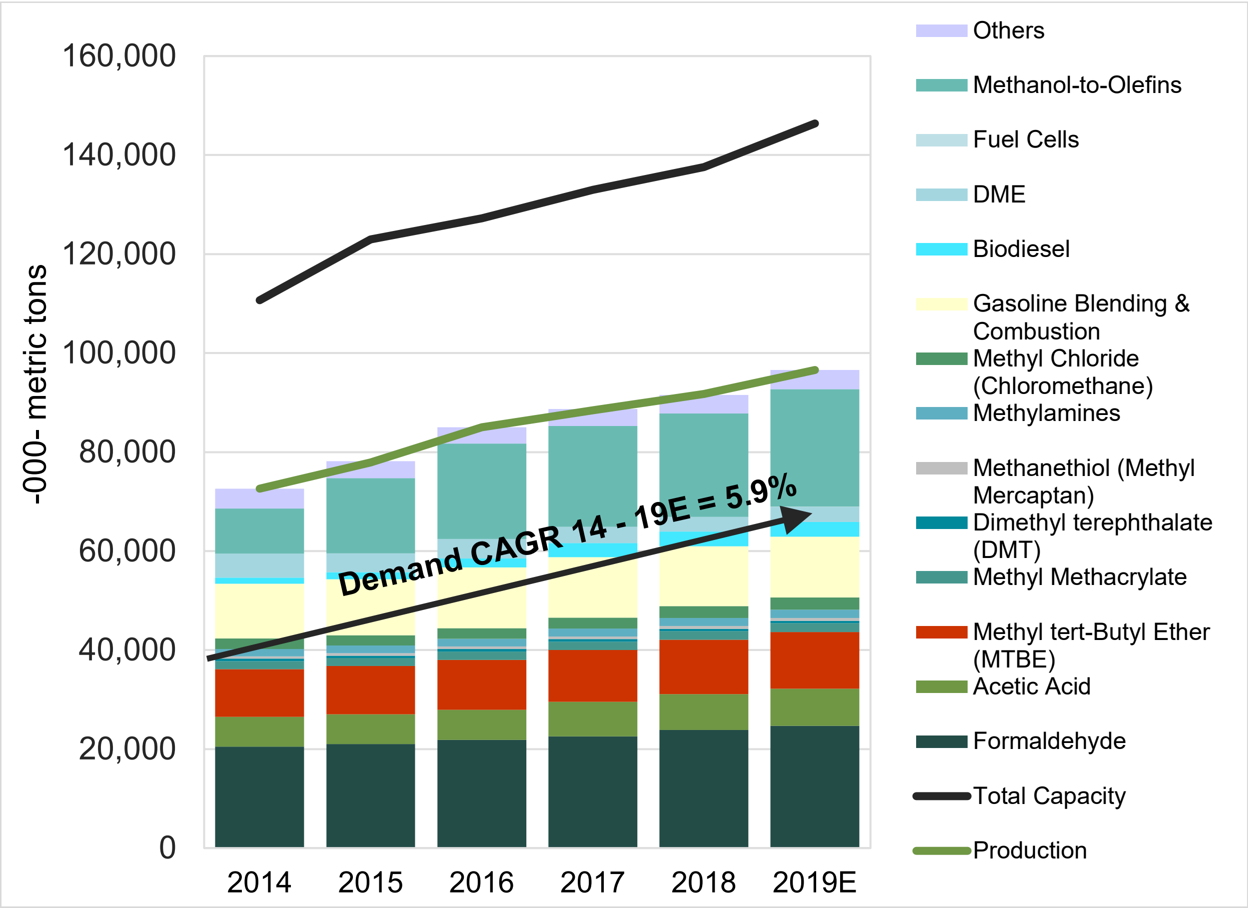
Polygeneration, the ability to scale efficiently and cost-effectively, versatility in so many products and applications including transportation fuels, its biodegradability and its 100-year history of safe production, use and handling is what makes methanol future-proof. These attributes are especially critical in a world that is beginning to act more aggressively to reduce GHG emissions to combat climate change. Methanol made from renewable sources drastically cuts greenhouse gas (GHG) emissions by up to 95% and can play an important role in a world that is moving toward GHG emission reductions or total net carbon neutral fuels for the energy and transport sectors.[2] Methanol also enhances new technologies that are likely to be part of this net zero future such as electrofuels, hybrid electric and hydrogen fuel cell vehicles, and other advanced transportation fuels such as dimethyl ether (DME) and oxymethylene ether (OME).

Given how abundant and widespread renewable methanol feedstocks are, renewable methanol can often be produced from locally available resources, increasing energy security for countries that are dependent on imported petroleum products and improving their fiscal balances by mitigating their reliance on oil imports. This a powerful driver for developing methanol markets, including transportation fuels, in countries such as India and China. Combating air pollution and reducing GHGs to move toward achieving net zero emissions and decarbonize economies are two other extremely important drivers for methanol production and use.

The global methanol market has grown on average about 6% annually since 2014, shown in Figure 3. Energy-related applications for methanol are the fastest growing segments of methanol demand and now represent 40% of global methanol consumption. Methanol is one the world's most shipped chemical commodities and is one of the top five most widely traded chemicals in the world. It has been stored, transported and handled safely for over 100 years. Since it remains liquid at ambient temperature and pressure, the infrastructure required to deploy it as a fuel is largely in place: combustion engines, fuel cells and power blocks could easily and affordably be adapted to use methanol.

[2] Methanol Institute, Renewable Methanol Report, December 2018 at https://www.methanol.org/wp-content/uploads/2019/01/MethanolReport.pdf (hereinafter "Renewable Methanol report").

Figure 3: Global Methanol Supply & Demand Balance, 2014-2019E*



*Source: Methanol Market Services Asia (MMSA), 2019 *The 2019 figures are an estimate.*

Methanol's properties are shown in Figure 4.

Figure 4: Properties of Methanol

Molecular Weight	32.04 g mol^{-1}
Critical Temperature	512.5K (239°C; 463°F)
Critical Pressure	8.084MPa (78.5 atm)
Critical Density	0.2715 g cm^{-3}
Critical Compressibility Factor	0.224
Specific Gravity	
Liquid	
(25°/4°C)	0.7866
(20°/4°C)	0.7915
(15°/4°C)	0.7960
Vapour	1.11
Vapour Pressure	
20°C (68°F)	12.8 kPa (1.856 psia) (96 mm Hg)
25°C (77°F)	16.96 kPa (2.459 psia) (127.2 mm Hg)
Latent Heat of Vapourization	
25°C (77°F)	37.43 kJ mol^{-1} (279.0 cal g^{-1})
64.6°C (148.3°F)	35.21 kJ mol^{-1} (262.5 cal g^{-1})
Heat Capacity at Constant Pressure	
25°C (77°F) (101.3kPa)	
Liquid	81.08 J mol^{-1} K^{-1} (0.604 cal g^{-1} K^{-1}) (0.604 Btu lb^{-1} °F^{-1})
Vapour	44.06 J mol^{-1} K^{-1} [1] (0.328 cal g^{-1} K^{-1}) (0.328 Btu lb^{-1} °F^{-1})
Coefficient of Cubic Thermal Expansion	
20°C	0.00149 per °C
40°C	0.00159 per °C

Boiling Point	
760 mm Hg (101.3 kPa)	64.6°C (148.3°F)
Freezing Point	-97.6°C (-143.7°F)
Reid Vapour Pressure	32 kPa
Flash Point	
Closed vessel (TCC method)	12°C (54°F)
Open vessel (TOC method)	15.6°C (60.1°F)
Auto Ignition Temperature	470°C (878°F)
Viscosity	
Liquid	
-25°C (-13°F)	1.258 mPa s
0°C (32°F)	0.793 mPa s
25°C (77°F)	0.544 mPa s
Vapour	
25°C (77°F)	9.68 μPa s
127°C (261°F)	13.2 μPa s
Surface Tension	
20°C (68°F)	22.6 mN m^{-1}
25°C (77°F)	22.07 mN m^{-1}
Refractive Index	
15°C (59°F)	1.33066
20°C (68°F)	1.32840
25°C (77°F)	1.32652
Thermal Conductivity	
Liquid	
0°C (32°F)	207 mW m^{-1} K^{-1}
25°C (77°F)	200. mW m^{-1} K^{-1}
Vapour	
100°C (212°F)	14.07 mW m^{-1} K^{-1}
127°C (261°F)	26.2 mW m^{-1} K^{-1}
Heat of Combustion	
Higher heating value (HHV) (25°C, 101.325kPa)	726.1 kJ mol^{-1} (22.7 kJ g^{-1})
Lower heating value (LHV) (25°C, 101.325kPa)	638.1 kJ mol^{-1} [calc] (19.9 kJ g^{-1})
Flammable Limits (in air)	Lower 6.0(v/v)% Upper 36.5(v/v)%

Source: Methanol Institute

This primer provides a status report and overview of methanol and its current use in vehicle transportation fuels and its role in future fuels as well. Increasingly, methanol is being used around the world in several innovative applications to meet growing demand for energy, particularly in transport. Out of the ~83 million metric tons of methanol sold globally in 2019, energy and fuel uses represent 40% of total demand. Methanol is just as versatile when used as a transportation fuel. It can be used:

- In low-, mid- and high-level gasoline blends, or as substitute for gasoline with M100 (neat methanol);
- As an important component of biodiesel;

- As a potential fuel for diesel engines;
- As a feedstock for other derivative fuels such as DME;
- With ethanol to create cleaner, renewable low-carbon gasoline mixtures, such as A20;
- As an ultra-low or even no carbon electrofuel that can be either a diesel, bunker fuel or gasoline substitute; and
- As a hydrogen carrier fuel for fuel-cell and battery electric vehicles.

This primer is organized into the following sections that will review and discuss:

- Methanol's fuel quality benefits;
- Concerns about the use of methanol;
- The history of methanol's use in vehicle fuels; and,
- Future fuels and methanol.

Methanol's Fuel Quality Benefits

Key Points in This Section:

- Methanol has many desirable attributes which make it an excellent spark-ignition engine fuel, including high octane and improved efficiency.
- For refiners, the use of methanol allows for the expansion of gasoline supply over a greater number of vehicles, and the upgrading of regular gasoline to high premium grades by increasing octane.
- For automakers, methanol contains oxygen for cleaner fuel combustion, a lower boiling temperature for better fuel vaporization, and a higher blending octane for smoother burning with reduced "knock."

Methanol used in transportation fuels is growing. As the most basic alcohol, methanol is a versatile, affordable alternative transportation fuel due to its efficient combustion, ease of distribution and wide availability around the globe. Methanol is used in gasoline blends around the world at low (3-5%), mid (15-30%) and high (50-100%) volume percentages, as a diesel substitute for use in heavy-duty vehicles (HDVs) and as a marine bunker fuel.

Biomethanol blends are being used in countries such as United Kingdom and new, methanol-derived fuels such as A20, a 15% methanol-5% bioethanol blend, are being trialed in Italy. Methanol is also an important building block for future fuels such as dimethyl ether (DME), electrofuels and hydrogen. Methanol is even being used in Denmark to provide range extension for battery electric vehicles (BEVs). These trends and developments are discussed in the sections that follow.

Methanol's superior quality as a fuel already was well known from racetracks and use in speed motorcycles. It maximized power output from a given engine size. On the racetrack, methanol was also viewed as a comparably safer fuel than gasoline. After a severe crash with gasoline-fueled cars in the Indy-500 race in

1964, gasoline was replaced by methanol, eliminating fuel-related fatalities. In 2005, Indycar changed from methanol to ethanol, a result of strong lobbing from the ethanol industry.[3]

Methanol has several physical properties that make it an ideal transportation fuel. For refiners, the use of methanol allows for the expansion of gasoline supply over a greater number of vehicles, and the upgrading of regular gasoline to high premium grades by increasing octane. For automakers, methanol contains oxygen for cleaner fuel combustion, a lower boiling temperature for better fuel vaporization, and a higher blending octane for smoother burning with reduced “knock.”[4] Methanol other desirable attributes that make it an excellent spark-ignition fuel which are summarized in Table 1.

Table 1: Methanol Attributes and Their Relevance[5]

Attribute	Relevance
Lower nitrogen oxides (NOx) and particulate matter (PM)	NOx is a component of ozone air pollution which can produce harmful health effects; PM is an air pollutant that is classified as a known human carcinogen by the World Health Organization (WHO)
Lower combustion temperature	Results in lower NOx emissions
Higher volatility	Better distribution among cylinders of air-fuel ratios and mass of fuel per cycle of multi-cylinder carburetor engines
Lower lean flammability limit	Lean mixture application and, consequently, better fuel economy and lower emissions of NOx, hydrocarbon (HC) (an air pollutant that contributes to ozone) and carbon monoxide (CO) (a toxic air pollutant)
Higher heat of evaporation	Leads to higher temperature drop in the Venturi nozzle of the carburetor and therefore higher volumetric efficiency
High octane	For refiners, reduce process energy consumption; for automakers, cleaner fuel combustion, better vaporization and reduced engine knock
Increased engine efficiency	Improved fuel economy with fewer modifications to the engine are expected when methanol is used in SI engines
Vapor pressure	Vapor pressure is not a problem for high blends of methanol; for low blends it can easily be handled by adjusting the before oxygenate blending (BOB) at the refinery
Comparable distillation characteristics to gasoline	Distillation characteristics of hydrocarbons have an important effect on their safety and performance, especially in the case of fuels and solvents. The boiling range gives information on the composition, the properties, and the behavior of fuels during storage and use. Volatility is the major determinant of the tendency of a hydrocarbon mixture to produce potentially explosive vapors. Distillation affects starting, warm-up and tendency to vapor-lock at high operating temperatures or at high altitude, or both. The presence of high boiling components in these and other fuels can significantly affect the degree of formation of solid combustion deposits.

[3] Ingar Landälv, Methanol as a Renewable Fuel – a Knowledge Synthesis, Report No 2015:08, 2017 available at www.f3centre.se (hereinafter "F3 Report").
[4] Methanol Fuels, Methanol Fuel Blending at https://methanolfuels.org/fuel-blending/ (last accessed Aug. 15, 2019).
[5] See SGS Inspire, “Methanol: Properties and Uses,” Dec. 23, 2019 at 8 (hereinafter “SGS Inspire”). See also Verhelst, et. al, "Methanol as a Fuel for Internal Combustion Engines," Progress in Energy and Combustion Science, https://doi.org/10.1016/j.pecs.2018.10.001 (hereinafter "Verhelst").

Attribute	Relevance
Existent gums	No existent gums which means no induction system deposits and sticking of intake valves providing for optimal engine operability
Biodegradabiity	Methanol is readily biodegradable in both aerobic and anaerobic environments, with a half-life in surface and groundwater of just one to seven days making it a safer and more environmentally benign fuel.

Source: Compiled by Future Fuel Strategies, February 2020

The sections below delve further into octane, engine efficiency, vapor pressure, distillation, existent gums and biodegradability.

Octane Contribution

Methanol blending provides a large octane contribution to refiners that can then reduce process energy consumption.[6] For automakers, methanol contains oxygen for cleaner fuel combustion, a lower boiling temperature for better fuel vaporization, and a higher blending octane for smoother burning with reduced "knock." This last point has become a critical issue for the automotive industry, which is increasingly recognizing the benefit of using more alcohol. Methanol's high octane facilitates higher engine efficiencies to meet fuel economy goals.

Methanol also provides an incentive to the gasoline terminal blender to upgrade other low octane gasoline blendstocks available in the gasoline supply market. Methanol's blending octane values (BOV) are nominally 129-134 research octane number (RON) and 97-104 motor octane number (MON).[7] Figure 5 compares RON levels gasoline, ethanol and methanol and their blends. Methanol's actual BOV will vary depending on the octane of the gasoline base fuel and its composition. RON is approximately 100 when methanol is between 10 vol% and 25 vol%.[8] With lower methanol concentrations in gasoline, RON decreases up to around 98.5.

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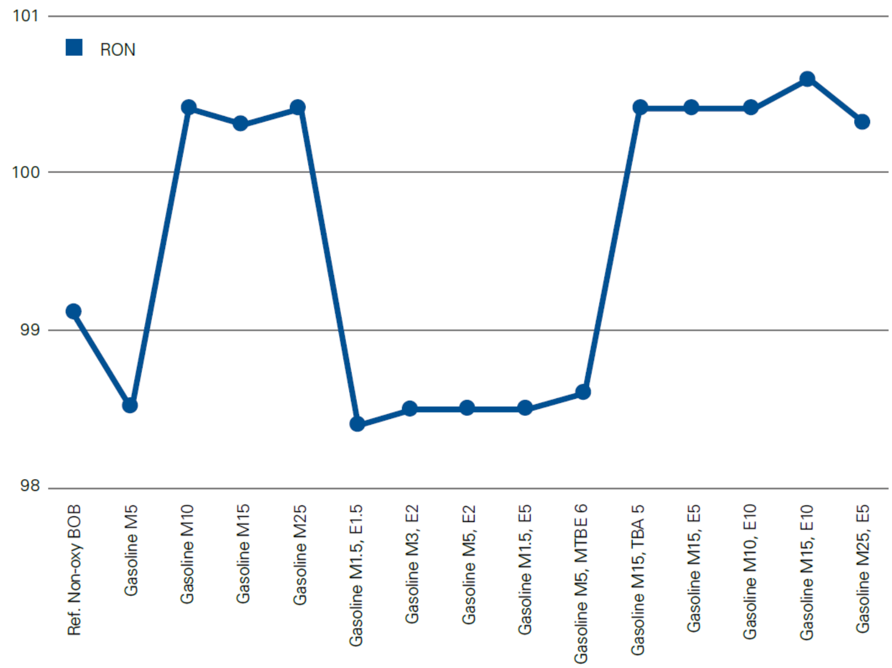
[6] Methanol Institute, "Methanol: Clean Burning High Octane from Non-Petroleum Energy," at methanol.org.
[7] Methanol Institute, "Methanol Use in Gasoline: Blending, Storage and Handling of Gasoline Containing Methanol," June 2016, p. 4 at http://www.methanol.org/wp-content/uploads/2016/06/Blending-Handling-Bulletin-Final.pdf (hereinafter "Methanol Use in Gasoline").
[8] See SGS Inspire at 27.

Figure 5: RON Levels for Gasoline, Methanol and Ethanol



Source: SGS Inspire, January 2020

The high BOV of methanol provides a convenient and cost-effective way to upgrade low octane gasoline components, such as low octane raffinate streams from BTX aromatic production units. For a refinery that is limited by octane capacity, each barrel of methanol added to the gasoline supplies can yield as much as 2.4 additional barrels of gasoline.

With one of the highest RON blending values available (higher than that of ethanol, MTBE, toluene, reformate or alkylate), methanol is an excellent blending component in all grades of gasoline. A comparison of the typical RON blending values of methanol and other high-octane gasoline blending components are shown in Table 2. Fuel methanol blending with its lower boiling temperature is particularly well suited for blending in premium gasoline which tends to have most of its high-octane components (aromatics) concentrated in the higher boiling range of the gasoline product.

Methanol also provides an effective means of improving the octane of premium gasoline without increasing its already high aromatics and olefin content, which can contribute to performance problems in some vehicles and higher vehicle exhaust emissions. Unlike aromatics, the use of methanol for octane in gasoline has been shown to have environmental benefits, as methanol blends reduce HC, CO, PM and other exhaust emissions from most vehicles.

Improved Efficiency

Fewer modifications to the engine are expected when methanol is used in SI engines as compared to compression ignition (CI) engines. Low methanol blends do not require modifications. According to SGS Inspire, from a technical point of view, neat methanol may be a very good fuel for SI engines, especially in areas with a warm climate. The engine fuel system needs to be modified due to the lower calorific value and smaller stoichiometric air-fuel ratio of methanol for its combustion in comparison with gasoline. With this optimization a better engine efficiency may be expected, mainly due to:

- Application of a higher compression ratio (CR)
- Possibility of operation on a leaner mixture
- Recovery of the latent heat of evaporation in the heat balance of the engine.

The efficiency of an optimized methanol-fueled engine may reach 40%; for direct injection methanol engines, more than achieved by turbocharged diesel engines or gasoline hybrids."[9] SGS Inspire notes:

> *"The high compression ratio, high degree of turbocharging and aggressive engine downsizing enabled by the high effective octane number of methanol could provide an efficiency gain of 30%-35% (for combined city-highway driving) relative to conventional gasoline engines. An additional gain of around 10% can be obtained by using reforming of methanol to enable ultra-lean operation at low loads. The combination of these gains could thus potentially provide an efficiency gain of 40-45% for direct injection methanol engines. This efficiency gain is significantly greater than the typical 25-30% gain of turbocharged diesel engines and similar to that of a gasoline-electric hybrid or turbodiesel, at a much more affordable cost."*[10]

Vapor Pressure

Like other alcohols, methanol experiences azeotropic effects (non-ideal blending) with the vapor pressure of gasoline.[11] Therefore, even though neat or pure methanol has a low Reid Vapor Pressure (RVP) of about 32 kPa at 38 ºC, its blending RVP in gasoline can range from 200 kPa up to 800 kPa depending on the methanol concentration in gasoline. Most of the RVP increase from blending methanol in gasoline occurs with the first 3 volume percent of methanol.

When blending to RVP specifications, the refinery will need to remove some butane from the gasoline to compensate for the RVP increase from the first 3 volume percent of methanol in the blend. However, methanol blended above 3 volume percent produces little further increase in RVP response which makes this portion of the curve relatively flat. Therefore, for the methanol blended above 3 vol% in gasoline, little if any additional butane will need to be removed from the finished gasoline blend. The result is that the blended methanol above the first 3 volume percent displaces mostly gasoline produced from refining crude oil.

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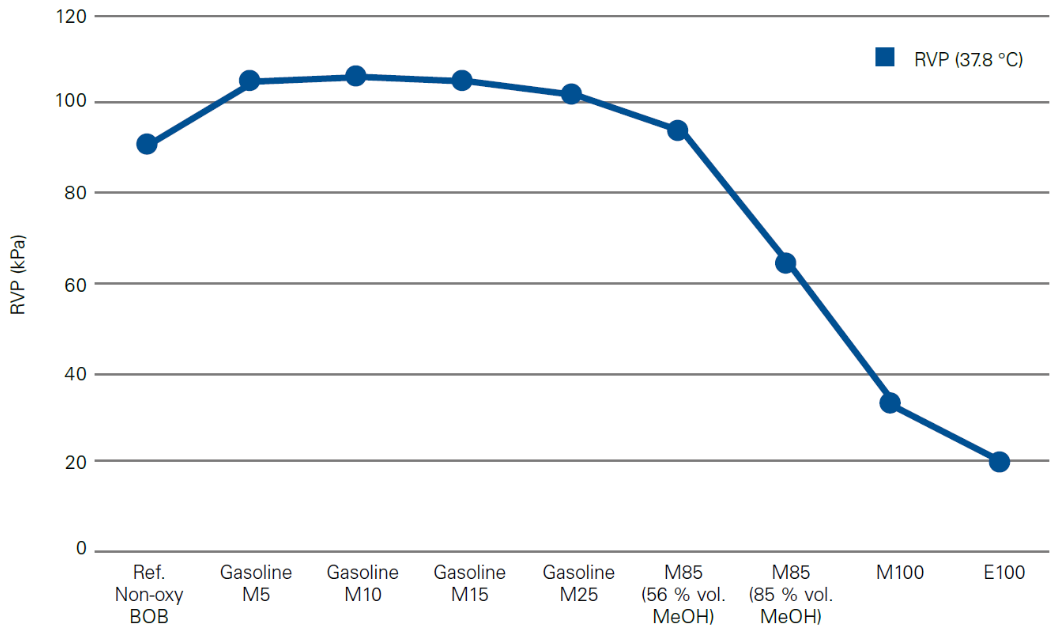
[9] See SGS Inspire at 9.
[10] Id. at 27.
[11] See Methanol Use in Gasoline.

Some co-solvent alcohols will need to be added to provide enough water tolerance and stabilize the gasoline blends under colder conditions. The co-solvent alcohols also provide some reduction in the methanol's RVP increase in gasoline and the amount will be dependent on the amount and the type of co-solvent alcohols added to the methanol blend. In general, higher carbon number alcohols such as butanol (C4) will provide greater reductions than lower carbon alcohols such as ethanol (C2) or propanols (C3).

SGS Inspire notes that, "vapor pressure is not a problem for high blends of methanol; for low blends it can easily be handled by adjusting the before oxygenate blending (BOB) at the refinery. A blend of 82 % methanol (M82) will result in a neutral vapor pressure, i.e. compliant with the EN 228 gasoline standard."[12] RVP values for gasoline and methanol are shown in Figure 6.

Figure 6: RVP Values for Gasoline and Methanol



Source: SGS Inspire, January 2020

Distillation

Like other alcohols, methanol blending produces an azeotropic effect on the distillation temperature curve of gasoline.[13] This produces a flattening or "knee" in the distillation curve of the blended gasoline that is just below

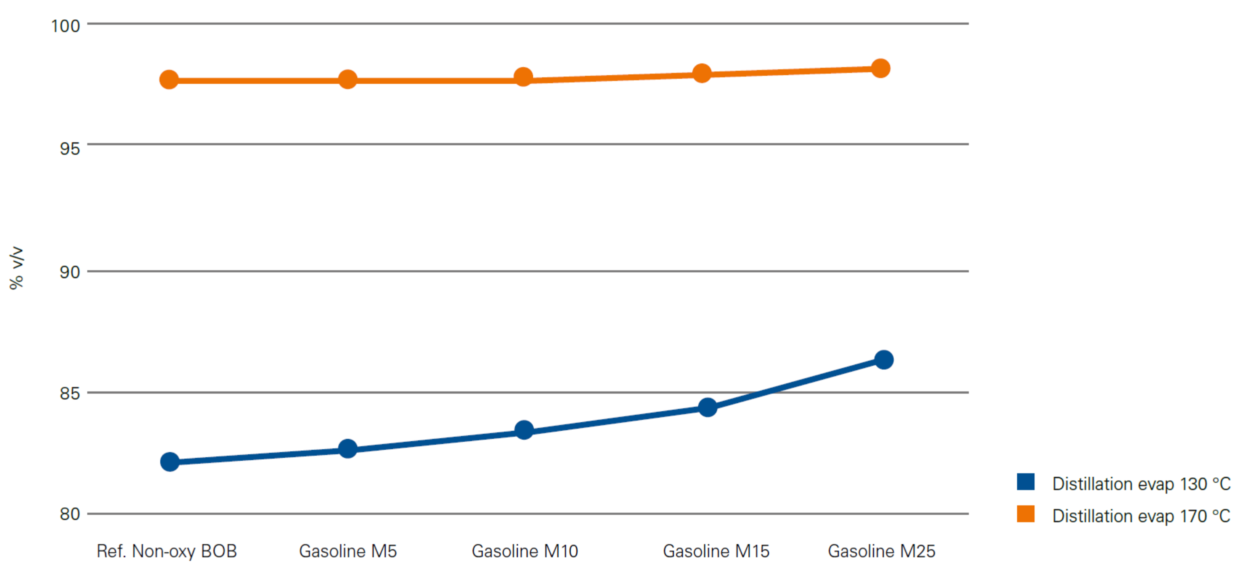
[12] See SGS Inspire at 25.
[13] See Methanol Use in Gasoline. The distillation curve is a universally used method to determine gasoline's volatility, or its ease of vaporization. For gasoline, the distillation test measures the percentage of vaporized fuel as the temperature increases. The test result is a "distillation curve" obtained under standardized conditions of temperature versus percentage of evaporated fuel where the different sections of the curve can interpret the different behavior of the gasoline. See also Fernández-Feal, et al., "Basic Test in Quality Control of Automotive Fuels," Apr. 14, 2016 at

the boiling point temperature of the alcohol being added (64.6 ºC for methanol). In general, adding more alcohol will increase the amount of knee or flattening at a point in the distillation curve of the gasoline blend just below the boiling point of the alcohol. The gasoline distillation curve impacts the drivability performance of the vehicle, particularly for older carbureted fuel system that essentially operated near atmospheric pressure. The percent evaporated at 100 ºC generally influences cold engine (warm up) drivability. The percent evaporated at 70ºC impacts hot engine (vapor locking) drivability with higher percentages making operation directionally worse, particularly for carbureted fuel systems.

However, in the last 20 years, the auto industry has mostly switched their vehicle production to fuel injector systems with their high pressure fuel systems which suppress fuel vaporization and thereby improves hot drivability performance and significantly dampens its sensitivity to the more volatile (lower) distillation temperatures associated with some gasolines and alcohol blends. Therefore, unlike past carburetor fuel systems, the modern fuel injector systems on today's vehicles allows a wider range of alcohol fuels to be used in the gasoline marketplace without experiencing a loss of vehicle operating performance.

According to SGS Inspire, gasoline-methanol blends evaporated faster at a lower temperature when methanol is added to gasoline.[14] Evaporation occurs also faster when the methanol content is above 15% vol. Figure 7 shows distillation evaporation values for gasoline and methanol.

Figure 7: Distillation Evaporation Values for Gasoline and Methanol



Source: SGS Inspire, January 2020

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https://www.intechopen.com/books/distillation-innovative-applications-and-modeling/distillation-basic-test-in-quality-control-of-automotive-fuels.

[14] See SGS Inspire at 22.

Existent Gum

High gum can cause induction system deposits and sticking of intake valves, and in most instances, it can be assumed that low gum will ensure the absence of induction-system difficulties. According to SGS Inspire, laboratory results suggests that methanol does not contain gum and high methanol blends barely any gums. "The conclusion we can draw from the laboratory results is that methanol does not contain gum, and therefore high methanol blends have barely none existent gum in the fuel. No other correlation can be drawn from the other samples; however, it does not have a significant meaning because below 5 mg/100 ml the gum content can be considered negligible."[15]

Methanol's Biodegradability and Air Oxidation

Besides being synthetically produced from many carbon-based energy sources, methanol is also a naturally occurring alcohol that is easily biodegraded in the environment.[16] Compared to common aromatics (benzene and toluene) used for adding octane to gasoline, methanol released into the environment has much shorter half-lives in soil and water mediums. In the case of a release into the air, methanol is more resistant to oxidation in the atmosphere, and thereby has much longer half-lives compared to gasoline, aromatics and ethanol. However, compared to other gasoline VOCs, methanol's resistance to air oxidation is also beneficial since slow oxidation of VOCs reduces the amount of ozone production that contributes to peak ozone exceedances.

Addressing Concerns about the Use of Methanol

Key Points in This Section:

- While methanol can be dangerous and toxic if not carefully and safely handled, the very same thing can be said of other alternative fuels, as well as gasoline and diesel.
- U.S. EPA found that methanol use is safer than gasoline — 30 years ago.
- There is more than 40 years of experience in using methanol in transportation fuels around the world.
- The issues raised with respect to the blending of methanol have either been resolved or are very manageable.
- Objections raised by the oil and some in the auto industry are at odds with policymaker goals to increase energy security, improve air quality and move toward decarbonization.

Various concerns have been raised about the use of methanol in transportation fuels over the years that include the following:

- Corrosivity and materials compatibility;
- Phase separation;
- Evaporative emissions;
- Energy content;
- Fire risks; and
- Toxicity.

Many of these concerns have morphed into objections to using methanol in any fuel application at all, but generally in high-, mid- and low-level methanol

[15] Id. At 12.
[16] Methanol Blending Guide at 27.

blends.[17] While there is no doubt that, for example, methanol can be dangerous and toxic if not carefully and safely handled, the very same thing can be said of other alternative fuels, as well as gasoline and diesel. As a matter of fact, from a fire risk perspective the U.S. EPA found nearly 40 years ago that methanol use is as safe as gasoline.[18] Consider the practical experience gained and technical advancement since then in:

- Handling, blending and distribution experience;
- Safety practices to reduce fire and toxicity risks;
- Development of additives such as corrosion inhibitors to reduce and eliminate corrosion and co-solvents to reduce the potential for phase separation;
- Advanced materials to reduce or even eliminate materials compatibility issues in vehicles; and
- Advanced port fuel injection system engines with computerized feedback control loops using oxygen sensors.

Each of these factors are considered further below.

Corrosivity and Material Compatibility

Some in the auto industry have in the past taken the position that methanol use should be limited because it is corrosive to metallic components and causes the degradation of plastics and elastomers in cars.[19] Of particular concern is the growth in use around the world in countries such as China.[20] Notably, the 6th edition of the Worldwide Fuel Charter, a statement from the global auto industry of the recommended fuels for different categories of vehicles released in 2019, found methanol acceptable for blending in gasoline where "specified by applicable standards," using the example of the European Union's allowance of up to 3% methanol by volume in gasoline under standard EN228.[21]

The compatibility of methanol and materials in a car's fuel system has been the subject numerous studies throughout the years. Methanol's polarity can cause issues of materials compatibility, which requires modifications to engine fuel systems. Both metals as well as elastomers (soft components used for seals and fuel lines) can be attacked by methanol, if not chosen properly.[22] This holds for all alcohols (such as ethanol, another widely used alcohol blended at levels as high as 85% in gasoline). Even so, there are no technical

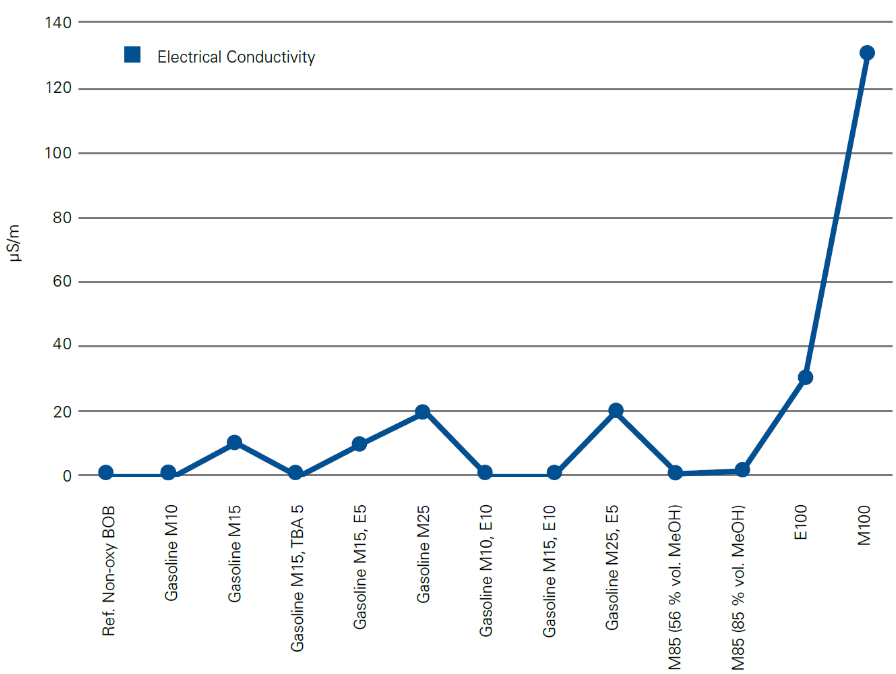
[17] F3 Report at 40. "The reason why methanol was ruled out of these applications is not clear, but it is well known that the oil majors had no interest in introducing methanol in the fuel market and that they often participated in conferences and workshops and expressed their negative view of methanol as a fuel. These activities were very intense in the years before and after 2000. The common arguments were: Methanol is toxic and methanol is corrosive. Both these arguments are of course true, but are they true to the extent that methanol should be ruled out of applications, since it might be a prime candidate if these two arguments were less stressed?"
[18] Paul Machiele, Flammability and Toxicity Tradeoffs with Methanol Fuels, SAE technical paper 872064 (1987).
[19] See e.g. European Automobile Manufacturers Association (ACEA), "ACEA Position Paper on Methanol as a Gasoline Blending Component," October 2015 at https://www.acea.be/publications/article/position-paper-methanol-as-a-gasoline-blending-component.
[20] Id.
[21] Worldwide Fuel Charter, 6th edition, October 2019 (hereinafter "WWFC").
[22] Verhelst at 67.

hurdles to design compatible vehicles which can be seen in major markets such as China. Methanol refueling systems at the service stations must also be designed with care. Tanks, pumps, lines and spigots should be alcohol compatible.

Light alcohols tend to be more corrosive to both ferrous and non-ferrous metals than gasoline. The polarity of methanol and ethanol causes dry corrosion, but often this corrosion is reinforced by ionic impurities such as chloride ions in the fuel.[23] As alcohols are hygroscopic, dissolved or separated water molecules can trigger wet corrosion phenomena. When using hydrous methanol as a fuel, special attention should thus be paid to this. Methanol is also electrically conductive. Corrosion behaviors that are dependent on conductive fluid behavior, such as electrochemical and galvanic corrosion, can be enhanced by an increase of the alcohol fuel's electrical conductivity due to absorbed water and contaminants.[24]

According to SGS Inspire, electrical conductivity for gasoline-methanol-ethanol blends has an average value of 10 µS/m. Pure alcohols have a much higher electrical conductivity, shown in Figure 8. SGS Inspire notes, "It can be observed that methanol or ethanol addition in gasoline does not have a significant impact on electrical conductivity despite the fact that ethanol, but particularly methanol, are electrically conductive."

Figure 8: Electrical Conductivity Values of Gasoline, Ethanol and Methanol



Source: SGS Inspire, January 2020

[23] See Yuen P.K.P, Villaire W, Beckett J. Automotive materials engineering challenges and solutions for the use of ethanol and methanol blended fuels. SAE paper no. 2010-01-0729; 2010.
[24] Id.

Alcohol fuels can be aggressive toward magnesium, aluminum and copper while steel and other ferrous metals are usually only slightly affected. For components that are in frequent contact with the fuel, austenitic stainless steel is often used, or other metals coated with a zinc or nickel alloy. Alcohol-rich fuels have been shown to cause shrinkage, swelling, hardening or softening of elastomers in the fuel system, particularly in higher methanol blends. For these applications, alcohol-compatible elastomer classes are used such as fluorocarbon elastomers or nitrile butadiene rubbers.[25]

Corrosion has been managed successfully for many years with the use of corrosion inhibitor additives and formulated engine oils. In fact, fuel samples tested by SGS Inspire in 2020 show no corrosion at all.[26] Further, the auto industry has upgraded vehicle fuel systems with more advanced materials that provide better durability and have switched to fuel injector (pressurized) systems with feedback control that can operate on a wider range of fuel distillation volatilities and oxygen levels in the fuel without experiencing significant changes in vehicle operating performance.[27] As a result of these fuel system improvements, most vehicles produced since 1990 perform well on properly blended methanol fuels containing sufficient co-solvents and corrosion inhibitors. The bottom line is that with the right choice of materials (metals and elastomers) and overall design of vehicles that are compatible with methanol, the materials compatibility issues associated with methanol can be managed and addressed. E15 is more accepted today and many vehicle models are compatible with higher levels of alcohol.

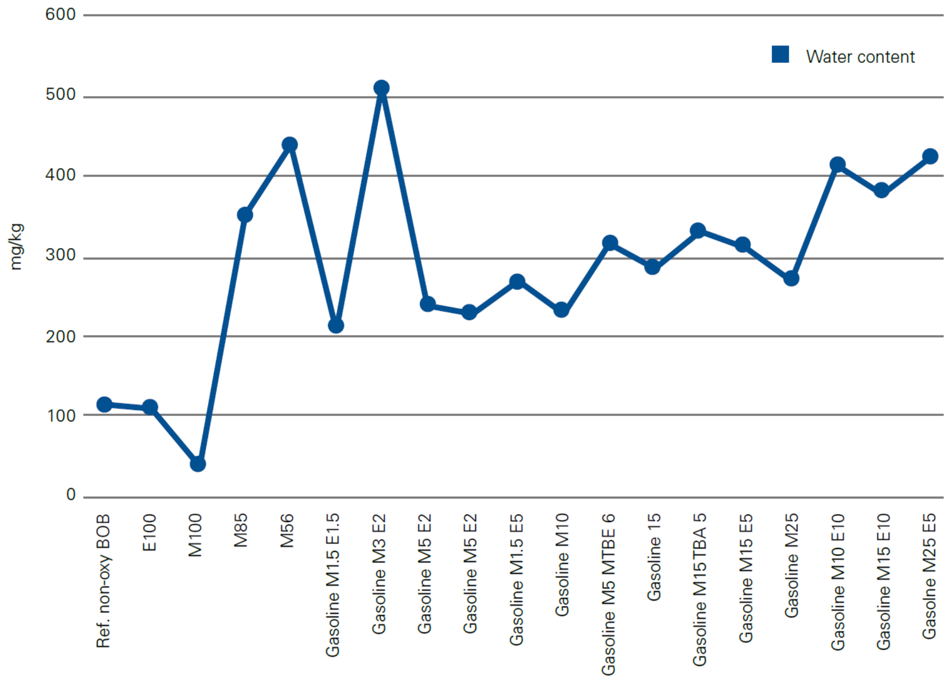
With respect to steel corrosion, fleet test results using terne[28] metal in the gas tanks have not shown any catastrophic failure of the tanks due to corrosion by gasoline/methanol blends under 15% methanol.[29]

Phase Separation

An important aspect of the storage of fuels is that the fuel must be stable. Gasoline is not miscible with water, unlike methanol (and ethanol), so blend stability becomes important. Cold start problems and knock resistance can occur. But this is easily addressed in methanol-gasoline blends with the addition of a co-solvent, such as ethanol. In fact, in testing conducted by SGS, water content was negligible in a range of blends, as Figure 9 shows.

[25] Id.
[26] See SGS Inspire at 14. "All samples tested in the laboratory had a result in the copper corrosion test of 1a, which means that there is no corrosion in the samples, just some light tarnish. In gasoline European standard EN 228:2012 + A1:2017, copper corrosion grade should be 1."
[27] Methanol Use in Gasoline at 9.
[28] Terne steel is sheet steel that is hot dipped in a tin-lead solution to retard corrosion, is almost exclusively used in current automotive fuel tanks. See SGS Inspire at 15.
[29] See SGS Inspire at 16.

Figure 9: Water Content of Gasoline, Ethanol and Methanol



Source: SGS Inspire, January 2020

SGS notes:

> *"With these results we cannot prove that water content is directly proportional to methanol content. The samples taken had a high purity and contain almost no water. It is possible that the water absorption showed in the results have taken place in the laboratory during storage of non-oxy gasoline. However, it is important to note that the water content in tested fuels is negligible."*[30]

In addition, good phase stability for methanol gasoline blends can be achieved with sufficient water tolerance (water solubility limits) and by implementing good water monitoring practices in the gasoline product distribution system.[31] Like other alcohol gasoline blends, the methanol blend will separate into two phases when exposed to amounts of water that exceed its water tolerance properties. The bottom phase will generally contain most of the alcohol and water along with some of the aromatics from the gasoline. This two-phase situation needs to be avoided, since the bottom phase can cause poor vehicle operation as well as contribute to corrosion of the metals in the fuel system.

Experience suggests that the methanol blend at point of production should have a minimum water tolerance of 0.15 volume percent in the gasoline blend at room temperature (21⁰C) to provide adequate protection from potential water exposure in the gasoline distribution system. The nearby chart shows higher methanol

[30] Id. at 31.
[31] Methanol Institute, "Methanol Facts: Methanol Gasoline Blends Require Good Water Monitoring Practices," November 2014.

concentrations provide increased water tolerance at 21^{0}C, but M15 (15% methanol) blends still fall short of the preferred water tolerance target. Experience over 30 years of commercial methanol/gasoline blending has shown that the water tolerance target for the M15 blend can usually be achieved by adding one to two volume percent of higher alcohols such as ethanol, propanol or butanol that act as co-solvents for the methanol in the gasoline. This has successfully been done by ENI and FCA with their A20 trial (see Future Fuels section below for more information on this trial). Lower methanol blends will produce lower water tolerances which will then require greater additions of co-solvent alcohols to achieve the targeted water tolerance property for the finished gasoline blend supplied to the retail market.

In addition to achieving targeted water tolerance properties in the methanol blend at point of blending, good water monitoring practices also need to be established in the gasoline distribution system from the point where methanol is first blended into the gasoline product. The gasoline distribution system from point of production at the oil refinery until it reaches the consumers' vehicle tanks at the retail market can potentially be complex, depending on the distance and terrain between the refinery and the retail gasoline market.

For quality control, there are generally two potential points for methanol to be blended in the gasoline. The preferred point is at the refinery gasoline operations, where the refinery can take full advantage of methanol's high octane and where there is also an on-site laboratory to ensure that the blend meets all gasoline specifications.

Because of lower quality control in terminal blending, some excess quality in terms of higher octane and lower RVP may need to be allowed in the finished gasoline blend. However, if the risk of water exposure cannot be controlled in the gasoline distribution system between the refinery and market terminals, then the methanol blending will have to be conducted at the market terminal and blended at the targeted volume concentration in the tank truck that delivers the finished gasoline to the retail stations. In this case, the refinery will have to produce a sub-octane and sub-RVP gasoline base fuel that is designed to meet the finished gasoline specification when the targeted concentration of methanol is blended into the delivery tank truck.

Evaporative Emissions

In the 6th edition WWFC, increasing evaporative emissions were raised as an objection to the use of methanol and methanol-gasoline blends.[32] A diagram of vapor emissions included in the draft assigned an unexplained 23 kPa higher fuel property for just the methanol fuel, which then unfairly created a very high running loss for the methanol fuel blend that is many factors higher compared to the E0 fuel base and the E10 ethanol blends that use much lower RVPs. However, since fuel regulations require that methanol fuel blends use the same industry fuel RVP standard as gasoline, there is no basis to use a high methanol blend RVP in this comparison that is much higher (+38%) than the 60 kPa for the E0 fuel. Assuming the same RVP, and other volatility properties for the methanol blend as the E0 base, there is no reason to expect a significantly higher running loss emissions for the methanol fuel blend as compared to the E10 ethanol blends at the same RVP.

[32] See WWFC at 31-32.

U.S. EPA has investigated[33] such concerns about vehicle evaporative emissions related to alcohol fuel blends and fuel volatility and determined that the evaporative emissions are generally related to volatility properties and not the alcohols in the fuel. As a result of their analysis of many studies, the U.S. EPA expected the evaporative emissions of the vehicle fleet (particularly fuel injected vehicles) not to be related to the use of any one alcohol in fuel blends if the volatilities are similar.

Energy Content

The energy content of methanol is lower than for gasoline and ethanol. Methanol's high oxygen content reduces the energy content (heating value). For low level methanol or ethanol fuel blends, the lower energy content of the alcohol is not significant, as the alcohol is simply displacing some or the volume of gasoline. For higher level blends where methanol or ethanol is being sold on an energy content basis, there will be a "Btu penalty," but even this can be reduced by optimizing engines to run on higher alcohol blends. The volumetric energy content is important for fuel injection system design and fuel storage.[34]

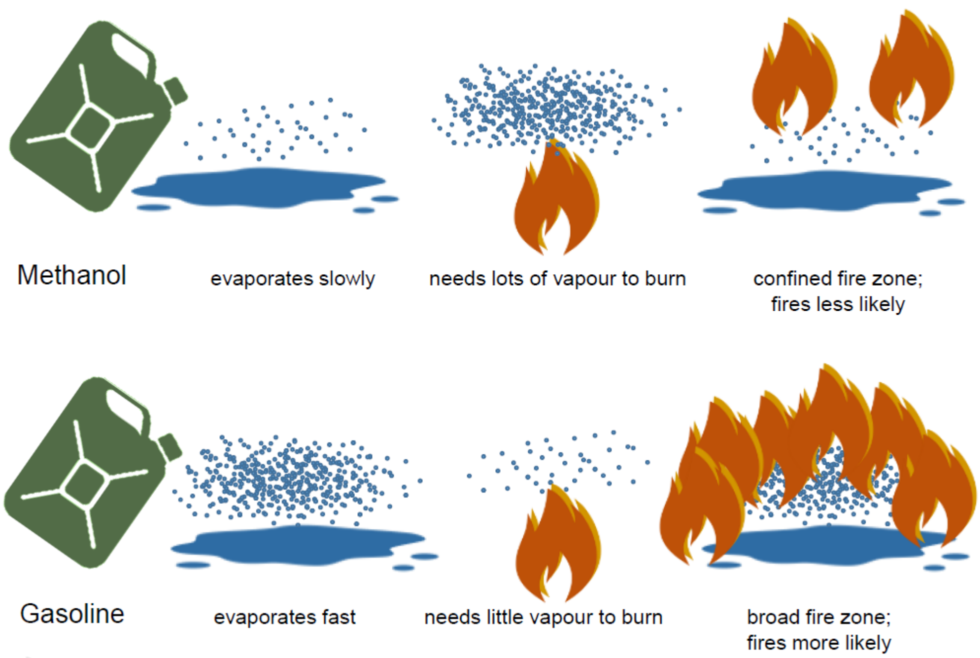
Methanol's higher density is more than offset by a heating value less than half that of gasoline, thus the volumetric energy content is half that of gasoline and consequently injection durations need to be twice as long in order to introduce the same energy into the engine, thus necessitating suitable injectors. This also implies larger vehicle fuel tanks are needed for a similar driving range, or that with the same size of vehicle tank as a gasoline vehicle, driving range decreases and the driver will need to refuel more often. Note that increases in efficiency can alleviate this issue somewhat.

Fire Risks

Neat methanol burns with an invisible flame under bright daylight conditions when no other materials are burning, which can be a safety risk.[35] However, this is addressed with blended fuels that can provide flame luminosity, and indeed, this is a standard practice in many parts of the world. For example, when blends with ethanol, another alcohol widely used in transportation fuels, and/or gasoline are used, these will provide a visible orange flame.[36] Moreover, methanol shows clear advantages over gasoline when it comes to fire safety. First, it is not readily ignitable below 10 °C, and it has a similar flammability index to diesel.[37] Figure 10 compares the fire risks for methanol and gasoline.

[33] See U.S. EPA, "Study of Gasoline Volatility and Hydrocarbon Emissions from Motor Vehicles," EPA-AA-SDSB-85-5, US EPA, November 1985 and U.S. EPA, Draft Regulatory Impact Analysis, Control of Gasoline Volatility and Evaporative Hydrocarbon Emissions from New Motor Vehicles, July 1987.
[34] Verhelst at 54-55.
[35] IEA Advanced Motor Fuels, Methanol at https://www.iea-amf.org/content/fuel_information/methanol (last accessed Aug. 25, 2019) (hereinafter "IEA-AMF").
[36] F3 Report at 23.
[37] Paul Machiele, Summary of the Fire Safety Impacts of Methanol as a Transportation Fuel, SAE technical paper 901113 (1990). See also Verhelst at 51.

Figure 10: Methanol v. Gasoline Fire Risks



Source: Methanol Institute

When compared to gasoline, methanol has a lower volatility, vapor density and heat release rate in a pool fire, the latter being about 11% that of gasoline. It also requires a greater concentration to form a combustible mixture in air. Another advantage of methanol, however, is that thanks to its miscibility, pure methanol fires can be extinguished with water. The inherent fire safety factors of methanol were the primary reasons why neat methanol was the fuel of choice for racing in the U.S. for decades until it was replaced by E85. Methanol may be considered even as a safer fuel than gasoline, harder to ignite, slower burning, and producing one-eighth the heat of gasoline.[38]

Methanol must be handled carefully just like other transportation fuels and chemicals. For example, due to the flammability of methanol vapor, static electricity may ignite it.[39] Therefore, grounding and bonding should always be applied when there is a potential for static electricity and is required for all equipment. Carbide-tipped clamps (to ensure good contact through paint) and dip tube filling are generally used to guard against ignition from static electricity. There are other common-sense measures that can be taken as well: prohibiting smoking, ensuring proper ventilation, grounding lightning and remediating any spills quickly.[40]

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[38] See IEA-AMF.

[39] For the definitive guide on toxicity and safe handling of methanol, see Enrique Medina, et al., "Methanol Safe Handling Manual," March 2017 p. 61 at http://www.methanol.org/wp-content/uploads/2017/03/Safe-Handling-Manual.pdf (hereinafter "Methanol Safe Handling Guide").

[40] For a complete list, see id. at 63.

Toxicity

Humans are exposed to methanol from many sources.[41] Not only does methanol occur naturally in the human body, but humans are exposed routinely to methanol through air, water, and food. Food is the primary source of exposure for the general population. It is generally believed that dietary sources contribute to the observed background blood methanol concentrations. Methanol is widely found in small concentrations in the human diet from fresh fruits, vegetables, commercial beverages like fruit juices, beers, wines, and distilled spirits. The food additives Aspartame (an artificial sweetener) and Dimethyl Dicarbonate (DMDC) (a yeast inhibitor used in tea beverages, sports drinks, fruit or juice sparklers), as well as wines, release small amounts of methanol when metabolized in the human body.

Refueling a fuel cell car with methanol will only give low-dose exposures (23-38 ppm for a few minutes), with a small intake of 3 milligrams of methanol. This is less than drinking a single can of diet soda containing 200 milligrams of aspartame, an artificial sugar containing methanol, which would produce 20 milligrams of methanol in the body. Methanol and gasoline have the same low health risk, and it is important to note that gasoline is a toxic fuel, and all transportation fuels need to be handled safely and should not be ingested.

The major issue alcohols including methanol face is toxicity from ingestion, skin or eye contact or inhalation. When this occurs, the concentration of the toxic intermediary products formaldehyde and formic acid becomes too high, and this is what causes health impacts to humans.[42] Ingestion is a concern. The amount of methanol that can cause severe methanol exposure is very small: Assuming that 100% methanol fuel is swallowed, the lethal dose is less than one teaspoonful (4 ml) for a one-year old infant, one and one half teaspoons (6 ml) for a three year-old child, and less than one ¼ of a cup (10-30 ml) for an adult.[43]

Symptoms of acute methanol poisoning from direct ingestion include dizziness, nausea, respiratory problems, coma and even death if untreated. However, the process takes between 10 and 48 hours after ingestion and treatment is well known, consisting of intravenous administration of ethanol, which the body preferentially metabolizes while the methanol is ejected. Accidental ingestion of methanol or ethanol or gasoline or diesel can be avoided by appropriate design of fuel dispensing systems.[44]

Skin or eye contact with methanol, as well as inhalation of methanol vapors are generally of much lower concern, if it does not persist for hours. The results of animal tests to determine the toxicity of various fuels by inhalation, oral and dermal contact have shown that the toxicity of alcohol fuels is comparable, and in many cases better than that of common gasoline or diesel.[45] Occupational (workplace) exposure is likely to cause the highest daily exposure to methanol, but this is relatively rare. It generally happens through inhalation of

[41] Id.
[42] Verhelst at 51.
[43] Methanol Safe Handling Guide at 55.
[44] Verhelst at 51.
[45] Id.

methanol vapors during production or use. Proper ventilation, exposure monitoring systems and personal protective gear can greatly reduce exposure risks related to inhalation.[46]

Finally, it should be noted that during the Californian M85 trial, which lasted for several years and involved 17,500 vehicles being used by the general public without special training in the refueling or use of gasoline/methanol FFVs, not a single issue of toxicity was reported.[47] Researchers have found that this is "clear empirical proof that methanol fuels can be deployed safely in the market."[48]

History of Methanol Blending in Fuels

Methanol blending into gasoline at low levels in the consumer market was first introduced in the mid-1970s in response to crude price oil shocks and the need to increase energy security. Because carbureted fuel systems were most prevalent in the vehicle fleets on the road at that time, and because those vehicles had limited ability to handle high oxygen levels in fuel, methanol blends were generally limited to 3 to 5 (M3-M5) volume percent of the gasoline blend. With today's modern pressurized port fuel injector (PFI) and gasoline direct injection (GDI) systems with computerized engine control units, experience has shown that methanol blends into gasoline as high as 15 volume percent (M15) can now be successfully used in the more modern vehicles that are on the road today.

Key Points in This Section:

- Methanol-gasoline blends are being used around the world, most notably in China, where demand continues to rise.
- Successful trials were carried out in California in the 1980s and 1990s with no health and safety incidents and where valuable experience and advancements in methanol blending were gained.
- Other countries are exploring the use of methanol as well.
- Methanol is a key component in the production of biodiesel.

Germany was one of the first country to test M15 blends. The auto and oil industries there conducted small vehicle fleet trials that lead to larger scale M15 blending in the country. Other countries that tested methanol at different levels during this time included: Sweden, Norway, New Zealand and China. Interest in blending waned in the mid-1980s as crude oil prices stabilized and ultimately crashed, remaining at low levels through the 1990s.

The California Experience

The state of California in the U.S. also conducted a methanol blend testing program for M85 in the 1980s that continued into the 1990s, despite the oil price situation. It was at that time the most extensive testing program in the world. During the program, 17,500 M85 flex-fuel vehicles (FFVs) including light-duty vehicles (LDVs) buses

[46] Methanol Safe Handling Guide at 59.
[47] Ward P, Teague J. Fifteen years of fuel methanol distribution. In: 11th Conference on Alcohol Fuels; Sun City, SA; 1996. p. 1-12.
[48] Verhelst at 52.

and trucks were successfully operated. In fact, the FFV, which can operate on any blend of gasoline and up to 85% methanol in the same fuel tank was invented for M85 during this time by Ford Motor Co. Today these flex-fuel vehicles generally operate on gasoline or gasoline-ethanol blends (up to E85). Over 200 million miles were driven in California using M85 with no health or safety incidents.

The state was interested in M85 from both an energy security and air quality improvement standpoint. The use of M85 delivered on both objectives. Reduction of unburned hydrocarbons (HC), nitrogen oxides (NOx) and particulate matter (PM) was significant. Further, the technically successful fleet trial in California showed that there were no real barriers to the introduction of methanol at high blend rates. If that was the case, then why didn't the M85 market take off? Low crude oil prices in the mid-1990s certainly contributed. But more fundamentally, the refining industry introduced reformulated gasoline using the methanol derived-component, methyl tertiary butyl ether (MTBE), which also achieved reductions in air pollution. As the state mandated reformulated gasoline, interest shifted away from alternative fuels generally, including M85. Evolutionary changes in engines and drivetrains, such as the promise of future Zero Emission Vehicles, was a contributing factor as well.[49]

The China Experience

In the early 2000s, the Chinese began to look for domestic alternatives to fuel their rapidly growing car fleet, which resulted in an ever-increasing cost of imported fossil oil.[50] Oil prices were rising again, which further incentivized the government to act. Since China has vast coal resources, methanol production based on coal gasification and its subsequent blending into gasoline became a natural fit. Promoting methanol as a vehicle fuel is line with the country's overall approach to utilize to the maximum its resources. Today, China is the largest consumer and producer of methanol in the world, and the price of methanol fuel is generally 30-50% lower than gasoline, while it is relatively inexpensive to retrofit vehicles to run on higher methanol blends, 500-1000 ¥ (US$73-$146).[51]

In 2002, Shanxi province launched a M15 demonstration program in four cities and Sinopec Shanxi was required to provide the M15 at its fueling stations. In 2004, the demonstration program was expanded to cover seven more cities. All cities were required to have at least 20 stations providing M15. In 2005, the cities of Yangquan, Linfen and Jincheng in Shanxi began to require M15 only and M100 demonstration in taxi fleets began.

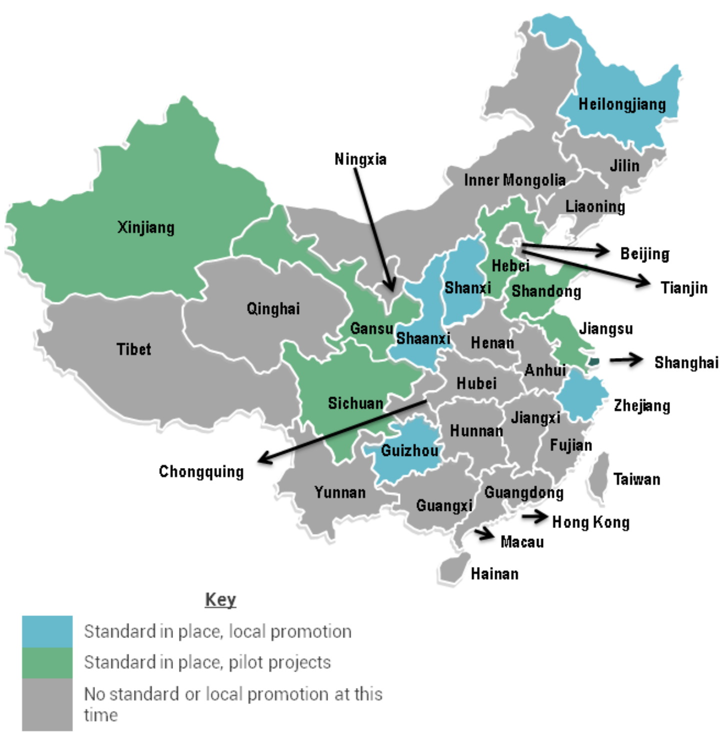
At the national level, the Ministry of Industry and Information Technology (MIIT) launched a M85 and M100 demonstration program in the provinces of Shanxi, Shaanxi and Shanghai in 2012 and then extended it to

[49] Paul Wuebben, A New Look at Methanol: Accelerating Petroleum Reduction and the Transition to Low Carbon Mobility, January 2016, p. 13 available at http://methanolfuels.wpengine.com/wp-content/uploads/2017/03/CA-Methanol-White-Paper-24-Oct.pdf.
[50] F3 Report at 14.
[51] Hao, et al., Coal-Derived Alternative Fuels for Vehicle Use in China: A Review, Journal of Cleaner Production, September 2016.

Guizhou and Gansu in 2014.[52] To date, 26 of the country's 33 provinces have participated in the demonstration program and many have local fuel quality standards governing the blending of methanol, shown in Figure 11 below. Blends in the market range from M5-M100. In 2009, national fuel quality standards for M100 and M85 were adopted.

According to the U.S. Energy Information Administration, 200,000 barrels per day (bpd) (or about 2.3 billion gallons) of methanol was blended directly into China's gasoline supply in 2016.[53] By the end of 2018, China had more than 1,200 filling stations with gasoline with a low proportion of methanol in Shanxi Province. There are 50 methanol gasoline blending terminal centers either completed or under construction in 15 Chinese provinces, and there is more than 1.2 million metric tons (or 400 million gallons) of annual methanol blending capacity.

Figure 11: Methanol in Chinese Provinces[54]



Province	Standard	Date Implemented
Gansu	M15, M30	2009
Guizhou	M15	2010
Hebei	M15, M30	2010
Heilongjiang	M15	2005
Jiangsu	M15, M45	2009
Liaoning	M15	2006
Ningxia	M15, M30	2014
Shaanxi	M15, M25	2004
Shandong	M15	2012
Shanghai	M5, M100	2013
Shanxi	M15, M85, M100	2008
Sichuan	M10	2004
Xinjiang	M15, M30	2007
Zhejiang	M15, M30, M50	2009

Source: Future Fuel Strategies citing data from the Methanol Institute, July 2018

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[52] Id.
[53] U.S. EIA, "International Data Revisions and the Short-Term Energy Outlook Forecast," February 2017.
[54] Ingvar Landälv, "Perspective on Methanol as a Transportation Fuel," November 2017, citing data from the Methanol Institute.

However, the Chinese government is planning to move away from M15 and toward M100.[55] In March 2019, eight ministries of China's central government led by the powerful Ministry of Industry and Information Technology (MIIT), issued a policy paper encouraging the expansion of M100 in the country. With this policy, Chinese customers can choose to purchase a methanol-fueled vehicle in the marketplace and register vehicles with no limitations. By contrast, there is a lottery and waiting list for gasoline-fueled vehicles that spans years. EVs are another option, but infrastructure and range can be an issue for some customers. The paper encourages policies that would encourage manufacturing of vehicles, production and fueling systems for methanol, standards setting, promoting methanol-fueled vehicles, among other measures.

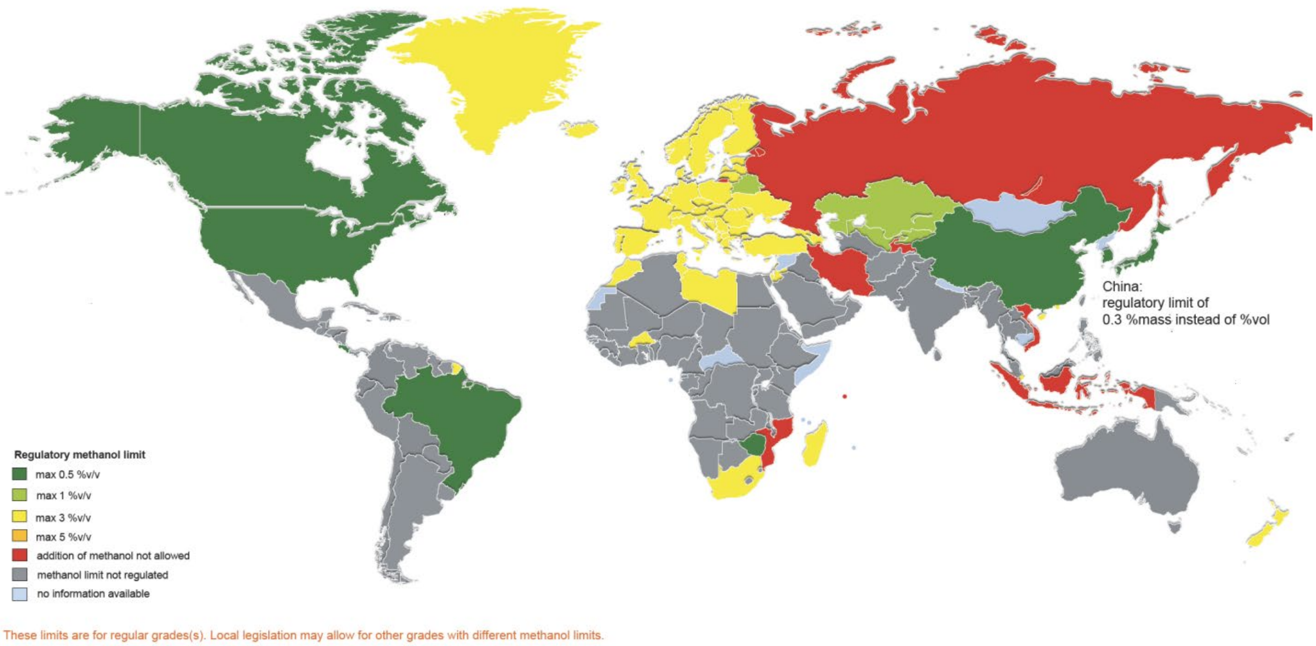
Meantime, major Chinese automakers such as FAW Group, Shanghai Huapu, Geely Group, Chang'an, Shanghai Maple and SAIC are already gearing up for mass production of methanol capable vehicles and fleets of buses and taxis. Geely founder Li Shiufu is particularly supportive of methanol while seeking to dominate the growing domestic and global electric vehicle (EV) markets as well. The company is also leading the development of M100 vehicles. Geely has two methanol engine and five methanol vehicle manufacturing bases with an annual methanol vehicle production capacity of 300,000-500,000 cars. Its M100 tax fleet reached 20,000 cars in June 2019, consuming 200,000 metric tons of methanol annually. M100 infrastructure is also being developed in China. For example, the cities of Guiyang and Xian each have 10,000 taxis and 20-30 M100 stations. These stations have 16 pumps and can consumer as much as 40 metric tons (13,000 gallons) of methanol per day.

Other Countries

Israel discovered natural gas reserves in its sector of the Mediterranean Sea in 2000 and has since then developed its domestic-based natural gas system, including establishing a national M15 standard in 2016 and allowing the blending of M15.[56] Other countries that are either introducing or evaluating the introduction of methanol blending in gasoline include Egypt, India (M15), Italy, New Zealand and Trinidad (M5). In India, the government has rolled out M15 with the goal to replace 20% of crude oil imports from methanol and reducing fuel costs by 30%. This would create a potential methanol demand of 5 million metric tons annually. Many countries have implemented methanol blending standards for low-level blends (M3-M5), including the European Union and the U.S. as Figure 12 shows.

[55] Methanol Institute, "China Issues Methanol Vehicle Promotion Policy," Mar. 19, 2019.
[56] F3 Report at 28.

Figure 12: Regulatory Limits for Methanol in Gasoline



Source: SGS Inspire, July 2019

Methanol as a Key Component of Biodiesel

In the process of making biodiesel fuel, a substitute for diesel fuel, methanol is used as a key component in a process called transesterification, which reacts methanol with the triglyceride oils contained in vegetable oils, animal fats, or recycled greases, forming fatty acid methyl esters (FAME or biodiesel) and the byproduct glycerin. Biodiesel production continues to grow around the globe, with everything from large-scale commercial operations to smaller, backyard blenders mixing this environmentally friendly fuel for everyday use in diesel engines. Biodiesel is blended in many countries around the world in low-, mid- and high-level blends up to B100.

Methanol as a Future Fuel

Key Points in This Section:

- Fuels of the future must be environmentally and economically sustainable, reduce or even eliminate GHG emissions and eliminate air pollutant emissions as well. The fuels that do will be "future proof." Methanol when produced from renewable biomass feedstocks, ticks these boxes, as do other methanol-derived future fuels such as ~~electrofuels,~~ DME, OME and hydrogen for fuel-cell electric vehicles (FCEVs) and battery electric vehicles (BEVs).
- As an “electrofuel,” Renewable methanol reduces carbon emissions by 65 to 95% depending on the feedstock and conversion process. That’s one of the highest potential reductions of any fuel currently being developed to displace gasoline, diesel, coal and methane.
- Electrofuels are an exciting prospect because of their potential GHG benefit, low to no land use issues (unlike some biofuels), no air pollution issues (e.g. NOx and PM), as well as their compatibility with fueling infrastructure and existing legacy vehicles.
- Interest in and blending of DME for heavy-duty vehicles is growing.

Growing recognition of the threat posed by man-made climate change has spurred government institutions, industry and science to find clean fuels to power economic activity. In this context, renewable methanol has risen as a clean alternative to fossil fuels, offering a clear pathway to drastically cutting emissions in power generation, overland transportation, shipping and industry.

But, it's not just about cleaner fuels. It's about finding fuel alternatives, especially in transport, that reduce GHGs substantially, even up to 100%, to achieve net zero (and even net negative emissions) otherwise known as decarbonization. Decarbonizing transport is becoming an increasingly important goal of governments around the world. And, with many policymakers and advocates viewing climate change as an emergency and an existential threat to the planet, the search for low-carbon, carbon-neutral and/or carbon-free energy and transport options to move a growing global population around has never been more critical.

Fuel and transport alternatives not only need to achieve net zero GHG emissions, they will have to reduce or even eliminate air pollutant emissions such as NOx and PM, be environmentally and economically sustainable. Fuels of the future must be able to tick all four of these boxes, and the fuels that do will be "future proof." Methanol when produced from renewable biomass feedstocks, ticks these boxes. So do other methanol-derived future fuels such as ~~electrofuels,~~ DME, OME and hydrogen for fuel-cell electric vehicles (FCEVs) and battery electric vehicles (BEVs).

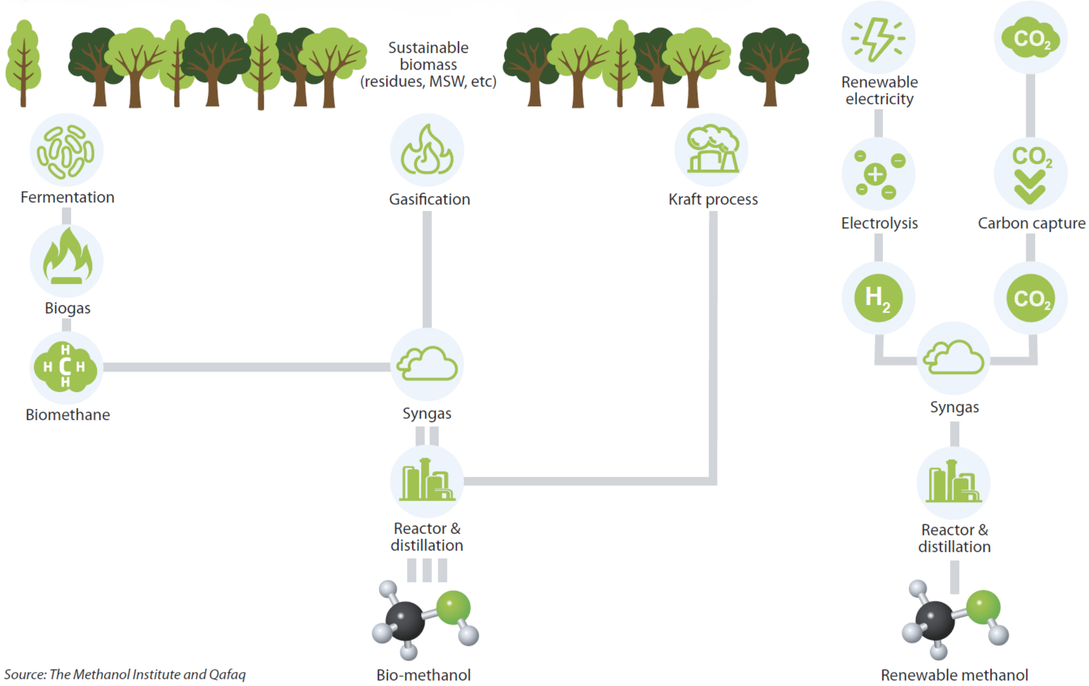
Renewable Methanol

Compared to fossil fuels, renewable methanol as an “electrofuel” reduces carbon emissions by 65 to 95% depending on the feedstock and conversion process. That’s one of the highest potential reductions of any fuel currently being developed to displace gasoline, diesel, coal and methane. Renewable methanol can be made from many plentiful sources which are available all over the world.[57] The necessary carbon molecules to make synthesis gas for methanol production can be obtained from CO2 from industrial process streams, or even captured from the air. Other sources include municipal solid waste (MSW), agricultural waste, forestry residues and renewable hydrogen. These are some of the largest sources but not the only ones. There are several renewable methanol production pathways: electro-fuels, biomass and hybrid methanol:

- **Electrofuels**: Renewable electricity is used to extract hydrogen from water by electrolysis. Hydrogen is then reacted with CO2 captured from point sources (e.g. industrial process streams) or from the atmosphere.
- **Biomass**: Organic matter undergoes fermentation or gasification (subjecting the biomass to high temperature in the absence of air) to produce synthesis gas (syngas) that is processed in a reactor and formed into bio-methanol.
- **Hybrid bio-methanol**: Uses a combination of the two production methods, combining biogenic syngas with hydrogen from electrolysis.

These are summarized in Figure 13. With respect to transportation fuels, renewable methanol can substitute current low, medium and high conventional methanol blends. Through the electrofuel production process, it can be turned into a drop-in fuel for gasoline, diesel and marine engines.

Figure 13: The Renewable Methanol Production Processes from Different Feedstocks



Source: The Methanol Institute and Qafaq

[57] Renewable Methanol report at 6.

Renewable methanol from sustainable biomass sources is not theoretical. It is happening now in several countries such as Iceland, the Netherlands, Sweden and Canada:

- Swedish company **Södra** is building a plant that will produce bio-methanol from the raw methanol resulting from their pulp mill manufacturing. The company says this is part of a sustainable circular process that uses all parts of forest raw materials to the best possible effect. Once completed, the plant will produce 5,000 metric tons of bio-methanol every year. According to Södra, their bio-methanol reduces CO2 emissions by 99% compared to fossil fuels.

- Biochemical company **Enerkem** in Canada estimates that up to 420 million metric tons of unrecyclable waste could be turned into biochemicals, using their technology. Enerkem is building a plant in Rotterdam which will turn 350,000 metric tons of waste, including plastic matter, into 270 million liters of biomethanol every year. The company is already producing renewable methanol and ethanol in Canada. Based in Montreal, Canada, Enerkem is a cleantech company that produces clean transportation fuels and renewable chemicals from municipal solid waste (MSW).

  The firm was founded in 2000 with the aim of further developing and contributing to a strong circular economy. It provides an innovative and sustainable solution to the increasingly pressing environmental issues of waste management and supporting energy diversification through biofuels. The company's first flagship, commercial scale waste-to-biofuels facility is in Alberta, Canada, where it helps the City of Edmonton increase its waste diversion goal from 50% to 90%. The plant began producing methanol in 2015, using the city's non-recyclable and non-compostable waste. The plant is designed to process over 100,000 metric tons per year of unrecoverable waste otherwise destined for landfill into methanol. Enerkem's facility was certified in accordance with the International Sustainability and Carbon Certification (ISCC) system in 2016.

  Enerkem's technology is leading to partnerships around the world, as municipalities, waste management and petrochemical groups develop commercial models to reduce landfill waste while creating clean fuels and renewable chemicals that will help meet carbon reduction targets. The company is working in Quebec and Rotterdam to develop biorefineries and has signed an agreement in China to license equipment and technologies to be used in a joint venture that could see over 100 advanced biofuels facilities built in China by 2035.

- In Iceland, **Carbon Recycling International (CRI)** is capturing and reacting CO2 from geothermal power- generation with renewable hydrogen produced via electrolysis into renewable methanol. The Icelandic grid, powered by hydro and geothermal energy, provides green electricity for the process of splitting water into hydrogen and oxygen. More than 4,000 metric tons of synthesized methanol (known as Vulcanol) are produced annually. Vulcanol is a clean burning, high octane fuel that can used directly as a vehicle fuel or blended with gasoline. It can also be used as a feedstock for producing biodiesel or fuel ethers and as a hydrocarbon feedstock for further production of synthetic materials. CRI supplies it to companies in Iceland, Sweden, the Netherlands, the UK and China. CRI's renewable methanol does not use any fossil fuel inputs or agricultural resources as feedstocks. Vulcanol is certified by the ISCC system as an ultra-low carbon advanced renewable transport fuel with no biogenic footprint.

CRI's George Olah Renewable Methanol Plant is the largest carbon dioxide methanol plant in the world. The company is ranked among the fastest growing technology companies in Europe19, with turnover up 440% between 2013 and 2017. CRI has partnered with Geely Holdings and Zixin Industrial Co to promote and establish renewable methanol production facilities in China. Geely and CRI, in collaboration with local companies, have also conducted a long-term fleet test of Geely's 100% methanol powered cars in Iceland running on Vulcanol. The cars were driven over 150,000 kilometers during an 18-month period, and study participants reported virtually no difference in driving experience compared to regular gasoline or diesel fueled cars.

- **BioMCN** in the Netherlands is converting biogas into advanced second-generation bio-methanol. The company operates two methanol production lines with a combined capacity of 900,000 tons at its plant located in Delfzijl in the northeastern part of the Netherlands. The plant was originally constructed in 1974 but was later mothballed in 2005 due to the high cost of natural gas. In 2006, BioMCN was founded and acquired the plant with the aim of producing renewable methanol from glycerin. In 2015, BioMCN was acquired by OCI N.V. and continued producing renewable methanol from biogas. During 2017, BioMCN produced nearly 60,000 tons of renewable methanol which was primarily sold as a biofuel in the European transportation fuel sector.

  In response to global climate change concerns, the Netherlands has chosen to impose tighter environmental regulations on carbon emissions and has actively encouraged the use of anaerobic digestion plants to process organic wastes into biogas. Digester plants reduce GHG emissions through methane recovery and are operated by waste companies, industrial firms and farmers processing numerous different types of municipal, industrial and agricultural wastes.

  BioMCN has become a vital market participant in this new green economy by utilizing this biogas to produce renewable methanol. Today, BioMCN consumes more than half of all the biogas produced in the Netherlands and has begun to source biogas from neighboring EU countries. As the number of digesters and availability of biogas grows in the future, BioMCN expects its production of renewable methanol will grow and its reliance on conventional natural gas will decrease.

More about Electrofuels

What are "electrofuels?" Also known as Power-to-X fuels or eFuels, electrofuels are any chemical process stimulated by electricity that results in a fuel, either gaseous or liquid.[58] As noted above, electrofuels capture

[58] Power-to-X is a reference to the flexibility in liquid or gaseous fuels; sometimes you will see "PtL", which stands for Power-to-Liquid fuels, or "PtG", which stands for Power-to-Gas.

CO2 and electricity to produce drop-in diesel or gasoline, methanol, DME or other fuels that can be used in vehicles, airplanes, or ships. Ideally, these fuels would be made from surplus energy from renewable sources (generally wind, solar, hydro, geothermal) during times when generation exceeds demand to create zero-carbon or carbon-neutral fuels subsequently used to decarbonize the transportation and energy sectors.[59]

In energy (power generation), the fuel is used in applications such as gas turbines or fuel cells to regenerate grid power at a later time when electricity demand exceeds renewable generation, and for injection into gas infrastructure to lower the carbon profile of delivered gas. Conceivably then, electrofuels constitute a renewable, entirely carbon-neutral replacement for fossil fuels.

In recent years, solar PV, hydro and wind have grown to account for a significant part of the energy mix in many parts of the world and this trend is expected to continue as the world move toward decarbonization. These resources provide clean and affordable electricity, but maximum electric yield might not match peak demand. For example, a wind power plant might peak at 3 am when the wind blows strongly but there is little need for electricity. In this case, supply could outstrip demand and threaten to overload the electric grid.

When this happens, the transmission system operator (TSO) tends to disconnect the renewable resource to safeguard the integrity of the grid. As a result, renewable energy is wasted. In the energy industry, this is known as curtailment. Curtailment costs can escalate. TenneT, a TSO, paid close to 1 billion euros in 2017 to wind energy operators as compensation for curtailment in the area it serves in Germany.[60] In California, the grid operator states that, although only about 1% of solar energy is curtailed in the state, “during certain times of the year, it’s not unusual to curtail 20 to 30% of solar capacity”.[61] Instead of being wastefully curtailed, this electricity could be harnessed to generate renewable methanol, which could in turn be used to generate clean power or as a renewable fuel for cars and ships.

The price of electricity is one of the main cost drivers of renewable methanol,[62] and excess renewable energy tends to command low prices because it is dispatched when demand is at its lowest. Several companies are exploring the idea of harnessing excess renewable energy to obtain clean hydrogen from electrolysis. One of them is thyssenkrupp, which is also sourcing excess CO2 from industrial sources to create renewable methanol. A schematic of their production process follows in Figure 14.

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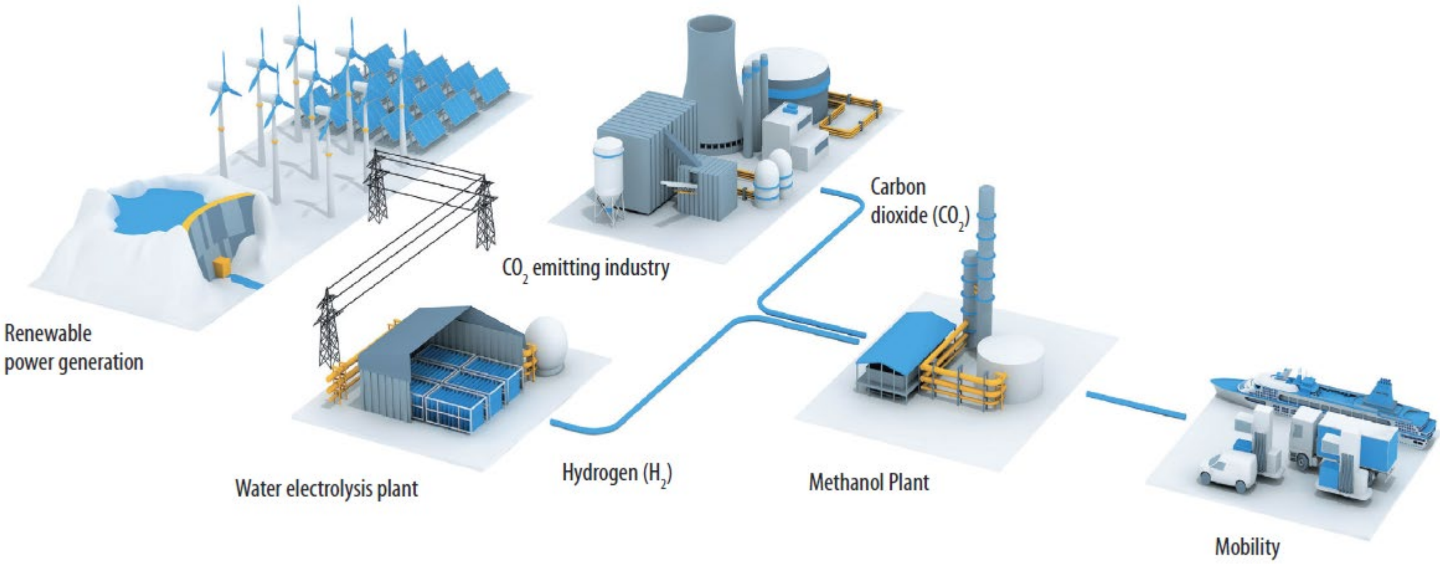
[59] David White, "The Coming of Electrofuels," Mar. 28, 2018 at https://www.linkedin.com/pulse/coming-electrofuels-david-white/.
[60] TenneT, Market Review 2017 at http://files.smart.pr/4d/76b0d038cf11e8b28c2defbda27260/20180405-Market-Review-2017.pdf
[61] California ISO, Impacts of Renewable Energy on Grids Operations at https://www.caiso.com/documents/curtailmentfastfacts.pdf.
[62] Liquid Wind Team of Sweden, Liquid Wind: Storing Energy by Making Fuel, May 2017 at https://www.innovatum.se/wp-content/uploads/2017/05/final-final-liquid-wind-report-may-2017.pdf.

Figure 14: thyssenkrupp's Concept of Using Renewable Energy and Waste CO2 to Make Renewable Methanol



Source: thyssenkrupp

The German government and car industry have started C3, an abbreviation for Closed Carbon Cycle, to research the feasibility of electrofuels from methanol, or e-methanol, as a building block for low carbon mobility.

Power grids would not only need to transition to renewables but would need to extensively expand to support electrofuels and other uses (e.g. overall power generation and substitution of fossil fuels, electric vehicles, etc.). This is one of the major issues with scaling up electrofuels. However, as the cost of renewable energy continues to decline and scale up globally, electrofuels are now more within reach as a real fuel alternative.

Some stakeholders in the auto industry are excited about the prospect of electrofuels because of their potential GHG benefit, low to no land use issues (unlike some biofuels), no air pollution issues (e.g. NOx and PM), compatibility with the fueling infrastructure and existing legacy vehicles. In fact, the auto industry in the EU is already advocating that the electrofuels GHG saving be counted toward meeting the EU Commission's more stringent LDV/HDV CO2 standards. Meantime, HDV, shipping and aviation advocates have said that electrofuels could be a viable solution for their respective sectors and, in fact, could be the most viable alternative long-term to fuel and decarbonize these sectors.

Dimethyl Ether (DME) and Oxymethylene Ethers (OMEs)

Dehydrated methanol, or dimethyl ether (DME or bioDME, when made from renewable sources), is a substitute for diesel fuel. DME for years has been used in the personal care industry as an aerosol propellant and is being used as a propane replacement in cooking gas in countries such as China. DME and bioDME can also be used as a replacement for diesel fuel in transportation. DME has a high cetane number and can therefore achieve higher engine efficiency, better mileage and emissions reductions.[63] It produces low PM and NOx emissions and handling is easier than for other diesel substitutes such as natural gas (LNG and/or CNG).

Like propane, DME is handled as a low-pressure liquid that can be easily shipped and stored. DME can also be used in some marine vessels. Fuel use of DME is not commercial today, but demonstrations are ongoing. However, in general there is no large-scale supply and distribution system for DME as a transport fuel. Oberon Fuels in the U.S. is currently operating a bioDME demonstration plant.

Requirements for modifications to the fuel distribution infrastructure and vehicle engine parts to accommodate the use of DME will influence the market introduction from bus and truck fleets to passenger diesel cars.[64] Ford is actively working with DME, and began the “xME for Diesel”-project funded by the German Ministry of Economy in 2015 to look at DME and OME1 (=Methylal or Dimethoxymethane) in passenger cars and heavy-duty applications. The company is also engaged in a project with Aachen University on fuel-generation paths (in particular, for electrofuels: CO2 + regenerative electricity => DME/OME1) to identify efficient fuel generation possibilities on small, medium and large production scales.[65]

Oxymethylene Ethers (OMEs)

Oxymethylene ethers (OMEs) are liquid fuels that can be combusted in conventional diesel engines and distributed using the existing fueling infrastructure. They can be used as drop-in fuels and could theoretically replace diesel fuel in transport, but particularly in the light- and heavy-duty vehicle fleets. A huge benefit of OME is that studies to date have shown low to nearly no NOx and PM emissions. Meantime, a recent lifecycle analysis has shown low GHG emissions depending upon the raw materials and production process used. Potentially, there is no trade-off between air pollution and GHG reduction as has been experienced with diesel fuel which is hugely attractive to the auto industry and why some companies are researching and testing OME.

Several studies are beginning to show that compared to fossil diesel, OME fuels have a higher oxygen content, leading to significantly lower PM emissions. This then enables further reduction of NOx emissions by increasing the rate of exhaust gas recirculation (EGR). Blending diesel fuel with a 20 vol% OME mix showed a soot reduction effect of about 50% at a NOx emission value of 0.25 g/kWh. The soot-NOx trade-off is completely avoided when using a neat OME mix. For this fuel the soot emissions remain below 0.1 mg/kWh even at 50% EGR. At a higher load, OME combustion shows an efficiency disadvantage due to its low lower-heating value in combination with an unadapted injection system. But by further increasing the injection pressure, a part of the efficiency drawback can be compensated.

Methanol as a Support for Fuel-Cell and Battery Electric Vehicles

[63] F3 Report at 32.
[64] Methanol Institute, "DME: An Emerging Fuel," available at http://www.methanol.org/wp-content/uploads/2016/06/DME-An-Emerging-Global-Guel-FS.pdf (last accessed Aug. 26, 2019).
[65] F3 Report at 34.

Fuel cells use hydrogen as a fuel to produce clean and efficient electricity that can power cars, trucks, buses, ships, cell phone towers, homes and businesses. Methanol is an excellent and efficient hydrogen carrier fuel, packing more hydrogen in this simple alcohol molecule than can be found in liquefied hydrogen (cooled to -252⁰C). Methanol can be "reformed" on-site at a fueling station to generate hydrogen for fuel cell cars or in stationary power units feeding fuel cells for primary of back-up power.

On-board reformer technology can be used on fuel cell vehicles, allowing quick three-minute fueling and extended range (from 200 km with hydrogen to 1,000 km on methanol). As a simple molecule – CH3OH – with no carbon-to-carbon bonds, Direct Methanol Fuel Cells (DMFC) can be used for some applications, where methanol reacts directly on the fuel cell's anode to strip hydrogen atoms to fuel DMFC systems. Since methanol can be produced from a wide range of conventional and renewable feedstocks, it is the most affordable, sustainable and easily handled hydrogen carrier fuel. There are several companies commercializing this technology including:

- Blue World Technologies (Denmark);
- Palcan (China);
- Horizon Energy Systems (Singapore);
- Oneberry (Singapore);
- Altergy (U.S.);
- SerEnegy (Denmark);
- SFC Energy (Germany);
- Toshiba (Japan); and
- Ultracell (U.S.).

Methanol can also support battery electric vehicles as well. For example, the Danish company Blue World Technologies produces methanol fuel cell range extenders to increase battery electric cars' range, allowing them to reach 1,000 km (621 miles), far beyond the rang of an average battery electric vehicle at this time.

Low Carbon Methanol

In recent years, several companies have developed technologies that reduce the carbon intensity of methanol produced from natural gas resulting in low carbon methanol (LCM). LCM is currently being produced by Methanex Corporation at its Medicine Hat, Canada plant. The company is doing this by injecting sequestered CO2 from a neighboring industrial facility into the methanol synthesis loop. This process significantly reduces GHG emissions when the LCM is utilized as a fuel. According to Methanex, a car that relies entirely on low carbon methanol would emit 30% less CO2 per kilometer, from well to wheel, compared to a gasoline-powered car.

Other methanol producers, such as Qatar Fuel Additives Company Limited (QAFAC), have implemented CO2 recovery plants to extract it from their flue gas (exhaustion gas) and re-inject it into the methanol production, reducing GHG emissions and water consumption. There are also other large-scale technologies for producing LCM from natural gas that yield similar emission reductions. Johnson Matthey, a technology licensing company, has developed a process called Advanced Combining Reforming that produces LCM by utilizing renewable electricity.

Policies to Support Renewable Methanol Applications and Low Carbon Methanol

There are government policies in place now or in the process of being implemented that require fuel producers to reduce the carbon intensity (CI) of their fuels. While bio-based fuels such as biodiesel and ethanol are commonly used to comply with these programs, other advanced, low carbon fuels are increasingly being used as they become more cost-effective and commercially available. Many of these fuels, especially renewable methanol and its different applications, are also attractive because they substantially reduce GHGs and produce no NOx or PM.

In total, over 60 countries have put renewable fuel targets or mandates in place, some with blending limits as high as 15 to 27%.[66] The EU, United Kingdom, Canada, the U.S. states of California and Oregon, and Brazil have implemented or are implementing low carbon fuel programs to require an annual CI reduction in fuels. These kinds of policies are helping to open the door for growing the renewable methanol market. For example, in the United Kingdom under its Renewable Transport Fuel Obligation (RTFO) renewable methanol is being used to meet targets. In 2018, 57 million liters of renewable methanol were blended into fuels representing 4% of total renewable fuel use in the country.

Two of the most far-reaching and ground-breaking policies that impact the use of renewable methanol are the EU's revised Renewable Energy Directive (REDII) and the U.S. Renewable Fuels Standards (RFS2) programs. Europe’s first biofuel policy was introduced in 2003, setting blending targets for 2010. This policy was integrated in the RED in 2009, which set an obligation of 10% renewable energy in transport for 2020. In 2018 the European Parliament, Council and Commission agreed to revise the RED, requiring 14% renewable energy to be used in transport by 2030. RED II has created new markets for conventional biofuels like ethanol and biodiesel and for alternative biofuels such as renewable methanol, especially when made from wastes, residues or renewable electricity.[67] Other EU policies also impact the potential uptake of renewable methanol: the Fuel Quality Directive, the Alternative Fuel Infrastructure Directive, and the Air Quality Directive, among others.

In 2007, the U.S. Congress enacted comprehensive energy legislation that included a Renewable Fuel Standard (RFS) program. It required a minimum volume of biofuels to be used in the national transportation fuel supply each year. The total renewable fuel requirement is divided into four separate – but nested – categories. These are: total renewable fuels, advanced biofuels, biomass-based diesel, and cellulosic biofuels, and each of these four categories has their own volume requirement that must be met each year. They also must meet a

[66] Jim Lane, Biofuels Mandates Around the World, Jan. 1, 2018 at https://www.biofuelsdigest.com/bdigest/2018/01/01/biofuels-mandates-around-the-world-2018/.
[67] European Commission, Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources.

specific GHG emission reduction thresholds, as shown in Table 2. Renewable methanol could meet either the cellulosic biofuel or advanced biofuel categories.

Table 2: Renewable Fuel Types, GHG Reduction Targets & Definitions

Renewable Fuel Type	GHG reduction target (in %)	Definition
Biomass-based diesel (BBD)	50%	"a renewable fuel that has lifecycle greenhouse gas emissions that are at least 50 percent less than baseline lifecycle greenhouse gas emissions and meets all of the requirements of this definition: (i) Is a transportation fuel, transportation fuel additive, heating oil, or jet fuel. (ii) Meets the definition of either biodiesel or non-ester renewable diesel. (iii) Is registered as a motor vehicle fuel or fuel additive."
Cellulosic biofuel	60%	"renewable fuel derived from any cellulose, hemi-cellulose, or lignin that has lifecycle greenhouse gas emissions that are at least 60 percent less than the baseline lifecycle greenhouse gas emissions."
Advanced biofuel	50%	"renewable fuel, other than ethanol derived from cornstarch, that has lifecycle greenhouse gas emissions that are at least 50 percent less than baseline lifecycle greenhouse gas emissions."
Renewable fuel	20%	"a fuel which meets all of the requirements of paragraph of this definition: (i) Fuel that is produced from renewable biomass. (ii) Fuel that is used to replace or reduce the quantity of fossil fuel present in a transportation fuel, heating oil, or jet fuel. (iii) Has lifecycle greenhouse gas emissions that are at least 20 percent less than baseline lifecycle greenhouse gas emissions."

Source: Environmental Protection Agency; Code of Federal Regulations

Other efforts to reduce GHG emissions in North America include the ongoing development of a Clean Fuel Standard (CFS) by the Government of Canada that is expected to be finalized in 2020 and the California Low Carbon Fuel Standard (LCFS), another ground-breaking program that was the first to require a specific CI reduction in fuels on an annual basis. The state of Oregon has implemented a similar program. The program has now expanded into the Pacific Coast Collaborative, a regional agreement between California, Oregon and British Columbia, Canada to strategically align policies to reduce GHGs by reducing the CI of fuels.

California's LCFS was established by executive order in 2007 and now requires a 20% reduction in the CI of transportation fuels by 2030. CI under the regulations is measured on a lifecycle basis expressed as grams of carbon dioxide equivalent per unit energy of fuel (gCO_2e/MJ). The regulated parties include providers of fuels and biofuels in the state; providers of natural gas, hydrogen and electricity may opt into the program.

The LCFS is designed to reduce GHG emissions in the transportation sector, which is responsible for about 40% of GHG emissions, 80% of ozone-forming gas emissions and over 95% of diesel PM. The need to reduce ozone and PM pollution in transport continues to be a major focus for the California Air Resources Board (CARB) as significant parts of the state are in nonattainment of the federal National Ambient Air Quality Standards for both ozone and PM. For CARB, finding low carbon substitutes that also reduce diesel PM, a carcinogen, is critical.

Lifecycle CIs for a range of different fuels or pathways have been developed and approved by CARB over the last few years. Essentially, the program has been designed to incentivize, in a fuel and technology-neutral way, the uptake of low carbon fuels. The lower the CI, the larger the premium that fuel captures in the state's fuel marketplace. Renewable methanol could be a valuable solution.

Gasoline, Ethanol and Methanol (GEM) Fuel Blends

There has been some experimentation with blending gasoline, ethanol and methanol also called ternary or sometimes, GEM fuel blends. The methanol could come from conventional or renewable feedstocks. With the ethanol and methanol produced from sustainable biomass sources, lower GHG and air pollution results. Another benefit is that these are "drop in" fuels, meaning GEM fuels are interchangeable and compatible with the fuel distribution network and vehicles. They can be used as is in vehicle and engines.

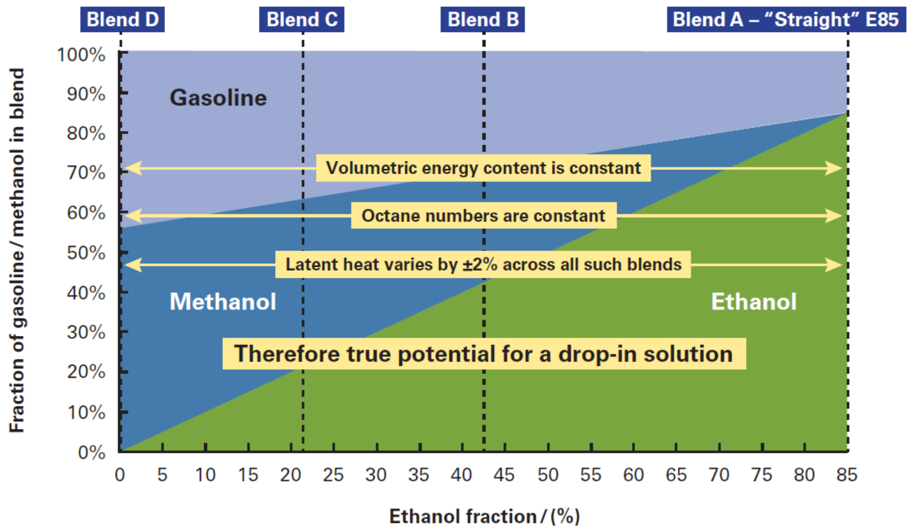
For example, Eni in Italy has developed a ternary fuel blend of 80% gasoline, 15% methanol and 5% ethanol that is being jointly tested with FCA.[68] The new fuel was successfully piloted in five Fiat 500 vehicles from the Enjoy fleet, Eni's car sharing service that was created in partnership with FCA, in an extensive road test that found the A20 blend to be "transparent" in E10 cars, with no material compatibility issues. Use of the GEM fuel blend was shown to reduce CO2 emissions by 4%.

Other experiments have shown even higher GEM fuel blends could be a viable substitute for gasoline that can be used in the existing flex-fuel vehicle (FFV) fleet globally with the stoichiometric air-fuel ratio (AFR) controlled to be 9.7:1. FFVs currently use a blend of gasoline and up to 85% ethanol. The combustion characteristics were similar as for E85.[69] When GEM fuels are blended to a target stoichiometric AFR, any of the blends possible share essentially the same volumetric energy content, RON, MON, sensitivity and latent heat (to within 4%). This is shown in Figure 15.

[68] Eni, Eni and FCA Have Developed A20, a New Fuel That Pairs Emissions Reduction with Energy Efficiency, Apr. 3, 2019 at https://www.eni.com/en_IT/media/2019/04/eni-and-fca-have-developed-a20-a-new-fuel-that-pairs-emissions-reduction-with-energy-efficiency#.

[69] See e.g., Turner, J., Pearson, R., Purvis, R., Dekker, E. et al., "GEM Ternary Blends: Removing the Biomass Limit by using Iso-Stoichiometric Mixtures of Gasoline, Ethanol and Methanol," SAE Technical Paper 2011-24-0113, 2011, https://doi.org/10.4271/2011-24-0113.

Figure 15: GEM Fuel Blend Testing Results



Source: J.W.G. Turner, R.J. Pearson, et al., "Evolution of Alcohol Fuel Blends Towards a Sustainable Transport Energy Economy," Lotus Engineering, Symposium White Paper, 2012.

Lotus also performed NOx emissions testing of these GEM blends. All GEM blends produced 10%–15% lower amounts of NOx than gasoline.

Methanol in Diesel Engines

There has been interest in finding ways to use methanol for compression ignition (CI) (diesel) engines. Methanol's high-octane number is an indication of its very low cetane number, the measure of a fuel's auto ignitibility.[70] For methanol the number is so low that it cannot be measured directly. But it could be used in conjunction with another fuel that is more auto ignitable or an ignition improver.

In the 1980s, the Detroit Diesel Company (DDC) and MAN produced modified versions of their CI engines which ran on "ignition improved" methanol fuel (the ignition improver constituted about 5% by volume of the fuel). The MAN engine was a four-stroke engine using spark-assisted ignition whilst the DDC engines operated on the two-stroke cycle, controlling the scavenge ratio to assist ignition. More recently, VTT has tested MD95, a mix of 95% methanol and 5% ignition improver. This was done using a Scania ED95 engine, which is an engine modified to enable compression ignition operation on a mix of 95% ethanol and 5% ignition improver through the adoption of an increased compression ratio (28:1, to increase end-of-compression temperature for easier ignition of the low cetane fuel), and a suitable fuel injection system.

A methanol-diesel dual-fuel approach, where each is injected directly in the combustion chambers, is a common approach that is being used commercially today. MAN uses it for low-speed two-stroke engines and Wärtsilä uses it for medium-speed four-stroke engines. There are other approaches as well. For example, glow plug ignition enables the compression ignition engine to run solely on methanol, without the requirement of a

[70] Verhelst at 72-73.

pilot fuel to serve as the ignition source.[71] Another solution, particularly when looking at retrofit options is introducing methanol into the engine's intake ports, which requires adding a low pressure methanol fueling system and port fuel injectors. Finally, very recently research engines have been run on methanol in homogeneous charge compression ignition (HCCI) mode and partially premixed combustion mode (PPC). Both concepts rely on delaying the autoignition until after the fuel injection event has been completed to allow for enough mixing time so that fuel-rich zones are reduced or eliminated, to decrease soot formation and speed up combustion for higher efficiency.[72]

Conclusion

Polygeneration, the ability to scale efficiently and cost-effectively, versatility in so many products and applications including transportation fuels, its biodegradability and its 100-year history of safe production, use and handling is what makes methanol a future-proof fuel. What also makes methanol future proof is its ability to reduce air pollution and GHGs. Renewable methanol, as it continues to scale up, will reduce GHGs by up to 95% and can be used in different applications in different transport sectors. Future proof fuels will have to tick the "GHG box" to remain viable in the coming years. Methanol can be a key fuel in a world that is moving toward "net zero" or total decarbonization of the energy and transport sectors.

Methanol enhances new technologies that are likely to be part of this net zero future such as electrofuels, hydrogen fuel cell vehicles, and other advanced DME and OME. Fuel and transport alternatives not only need to achieve net zero GHG emissions, they will have to eliminate air pollutant emissions such as NOx and PM and be environmentally and economically sustainable. Fuels of the future must be able to tick all four of these boxes, and the fuels that do will be "future proof." Methanol when produced from renewable biomass feedstocks, ticks these boxes. So do other methanol-derived future fuels such as electrofuels, DME, OME and hydrogen FCEVs and BEVs.

[71] Id.
[72] Id.