



Methanol as a Renewable Energy Resource

White Paper

**Prepared for:
Methanol Institute
124 South West Street, Suite 203
Alexandria, VA 22314**

Date: January 16, 2013

**Prepared by:
Karen Law
Jeffrey Rosenfeld
Michael Jackson
TIAX LLC
20813 Stevens Creek Blvd., Ste 250
Cupertino, CA 95014
Tel 408.517.1550
Fax 408.517.1551**

TIAX Reference No. D5632

Legal Disclaimer

This report was commissioned by the Methanol Institute on terms specifically limiting TIAX's liability. Our conclusions are the results of the exercise of our best professional judgment, based in part upon materials and information provided to us by the Methanol Institute and others.

TIAX accepts no duty of care or liability of any kind whatsoever to any third party, and no responsibility for damages, if any, suffered by any third party as a result of decisions made, or not made, or actions taken, or not taken, based on this document.

This report may be reproduced only in its entirety.

Acknowledgments

The authors gratefully acknowledge the assistance of Greg Dolan, Clifton Jackson, and Matt Roberts of the Methanol Institute, Michael Wang of Argonne National Laboratory, and the renewable methanol producers who provided their insights for this publication.

Table of Contents

Executive Summary	vii
1 Background	1
2 Renewable Methanol Pathways	3
Municipal Waste to Renewable Methanol	3
Industrial Waste to Renewable Methanol	3
Biomass to Renewable Methanol (Biomethanol)	3
CO ₂ to Renewable Methanol	4
Other Pathways	4
3 Renewable Methanol Pathway Emissions.....	6
4 Market Dynamics	9
Renewable Feedstock Availability.....	9
Production of Renewable Methanol.....	9
Economics	9
Policies and Regulations	11
Methanol Applications and Derivative Markets	12
5 Case Studies	15
BioMCN	15
Range Fuels.....	16
Carbon Recycling International	17
6 Conclusions	18

Executive Summary

As global concerns grow regarding energy security, air quality, and climate change, opportunities emerge for alternative fuels to displace the petroleum fuels on which today's transportation sector depends. One such alternative fuel is renewable methanol, a liquid fuel that has been demonstrated to be a successful replacement for gasoline and diesel. This white paper focuses on the options, benefits, and considerations for renewable methanol primarily as a transportation fuel.

Renewable methanol can be produced via four primary pathways: municipal waste, industrial waste, biomass, and carbon dioxide. The first three pathways rely on gasification and catalytic conversion technology to produce renewable methanol, while the fourth pathway produces methanol from carbon dioxide, water, and renewable electricity building blocks. Major worldwide producers that are currently employing these technologies include BioMCN (Netherlands), Blue Fuel Energy (Canada), Carbon Recycling International (Iceland), Chemrec (Sweden), Enerkem (Canada), and VärmlandsMetanol (Sweden).

A key benefit of renewable methanol is its potential to significantly reduce greenhouse gas (GHG) emissions from the transportation sector. Relative to conventional fuels on a well-to-tank (WTT) basis, producers estimate that renewable methanol offers carbon reduction benefits ranging from 65 percent to 95 percent. These GHG benefits are among the highest for alternative fuels that can displace gasoline and diesel. For the tank-to-wheels (TTW) portion of the full fuel cycle, methanol as a transportation fuel can offer two types of advantages over conventional fuels: lower tailpipe emissions in combustion and higher efficiency vehicle technologies. When used to fuel a combustion engine, methanol has been shown to emit 15 to 20 percent less carbon than gasoline. As an alternative to combustion, methanol can also be used in fuel cells, which are estimated to be 2.6 to 3.5 times more efficient than combustion engines for motive power; when fuel consumption is reduced, resulting tailpipe emissions are reduced as well. Together, the WTT and TTW GHG emissions of renewable methanol represent compelling benefits that can enable the transportation sector to meet ambitious carbon reduction goals.

The market dynamics of renewable methanol are driven by the scale of its production, its economics relative to competing fuels, policies and regulations regarding renewable fuels, and demand across methanol applications and derivative markets. Feedstock availability is an additional market driver, but in the case of renewable methanol, feedstock availability is not expected to be a primary limiting factor.

Case studies of BioMCN, Range Fuels (a previous renewable methanol producer), and Carbon Recycling International offer lessons for growing the renewable methanol industry. Key considerations that increase likelihood of success are: end-to-end supply chain partnerships, realistic timelines for scale-up of operations, clear communication about intended products, targeted market entry strategies, blending into current fuels for greater acceptability in the existing transportation market, and the ability to replicate the methanol production system.

Overall, renewable methanol may offer significant benefits in the carbon-constrained transportation and power generation markets. It is a viable option for reducing the greenhouse

gas impacts of energy use and merits further exploration and development in today's regulatory climate. The most promising efforts are still underway, and the renewable methanol industry is expected to encounter important decision points and milestones over the next several years.

1 Background

As global concerns grow regarding energy security, air quality, and climate change, opportunities emerge for alternative fuels to displace the petroleum fuels on which today's transportation sector depends. One such alternative fuel is renewable methanol, a liquid fuel that has been demonstrated to be a successful replacement for gasoline and diesel. This white paper focuses on the options, benefits, and considerations for renewable methanol primarily as a transportation fuel. In addition, renewable methanol is evaluated in the context of global methanol applications and derivative markets.

Renewable methanol refers to any type of methanol produced from a non-fossil fuel feedstock; renewable feedstocks include municipal waste, industrial waste, biomass, and carbon dioxide (CO₂). Biomethanol is the subset of renewable methanol produced from biomass feedstocks. As a transportation fuel, methanol offers several key advantages. It is a higher octane fuel than gasoline.¹ If spilled or leaked, methanol is biodegradable and less ecologically damaging than conventional fuels.² Depending on how the methanol is produced, its price at the pump may offer significant fuel cost savings for the end user compared to gasoline and diesel. As an alternative fuel, methanol offers increased energy security from the volatility of the worldwide petroleum market. On a full fuel cycle basis, methanol may offer criteria pollutant and greenhouse gas (GHG) emission benefits over conventional fuels, particularly if it is produced from renewable feedstocks.

However, as with any transportation fuel, the use of methanol entails tradeoffs. It has roughly half of the energy content of gasoline on a volume basis.³ Like ethanol, methanol is miscible in water and corrosive, requiring materials compatibility and distribution considerations different from gasoline and diesel. Methanol may not be able to fully replace conventional fuels in existing vehicles. However, low level blends of methanol in gasoline are already being used in various parts of the world in today's vehicles, and high level blends, including M85 and M100, are being used in vehicles designed to operate on methanol. Costs to modify today's engines for methanol are expected to be modest, estimated at approximately \$100 to \$200 more than ethanol-gasoline flex-fuel vehicles.⁴

In all, while methanol faces challenges in the transportation market, its extensive testing in the United States (U.S.) in the past, its current use in countries such as China, and its widespread applications in other non-transportation markets makes it a relatively familiar fuel. New availability of abundant natural gas around the world, especially in North America, suggests that

¹ Octane number of 89 of 109, compared to 80 to 100 for gasoline. Engineering ToolBox, "Alternative Fuels – Properties," http://www.engineeringtoolbox.com/alternative-fuels-d_1221.html, accessed September 2012.

² Difiglio, C. "Background: U.S. Alternative Fuel Policies and Methanol." U.S. Department of Energy, U.S.-Israel Energy Meeting. July 25, 2011.

³ Lower heating value of 57,250 Btu per gallon, compared to 113,602 Btu per gallon for reformulated gasoline. Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model, version GREET 1 2012.

⁴ Moniz, E.J., H.D. Jacoby, A.J.M. Meggs, R.C. Armstrong, D.R. Cohn, S.R. Connors, J.M. Deutch, Q.J. Ejaz, J.S. Hezir, G.M. Kaufman, M.A. Kenderdine, F. O'Sullivan, S. Paltsev, J.E. Parsons, I. Perez-Arriaga, J.M. Reilly, C. Seto, M.D. Webster, Y. Yang, G.S. McRae, C. Ruppel. "The Future of Natural Gas: An Interdisciplinary MIT Study." 2011.

methanol can be produced inexpensively from natural gas for transportation applications. Because a gaseous fuel presents difficulties in a liquids-based transportation system, major studies have recommended the use of methanol as a liquid natural gas carrier. A recent study performed by the Massachusetts Institute of Technology compares fuels into which natural gas can be converted that are room temperature, atmospheric pressure liquids and concludes that “methanol is the only one that has been produced for a long period at large industrial scale.”⁵ In China, abundance of coal that can be inexpensively converted to methanol is driving methanol’s use as a transportation fuel. An expanded methanol market based on fossil fuels can enable a transition to renewable methanol by establishing the necessary infrastructure and demand and allowing renewable methanol to be blended into existing methanol supplies in gradually increasing quantities.

⁵ Moniz, E.J., H.D. Jacoby, A.J.M. Meggs, R.C. Armstrong, D.R. Cohn, S.R. Connors, J.M. Deutch, Q.J. Ejaz, J.S. Hezir, G.M. Kaufman, M.A. Kenderdine, F. O’Sullivan, S. Paltsev, J.E. Parsons, I. Perez-Arriaga, J.M. Reilly, C. Seto, M.D. Webster, Y. Yang, G.S. McRae, C. Ruppel. “The Future of Natural Gas: An Interdisciplinary MIT Study.” 2011.

2 Renewable Methanol Pathways

Renewable methanol can be produced via four primary pathways: municipal waste, industrial waste, biomass, and CO₂. The first three pathways rely on gasification and catalytic conversion technology to produce renewable methanol, while the fourth pathway produces methanol from CO₂, water, and renewable electricity building blocks. Each pathway is described below, and key global producers known to be actively implementing these pathways are identified.

Municipal Waste to Renewable Methanol

In the municipal waste pathway, waste materials such as trash and construction materials are gasified to produce syngas, which is then catalytically converted to methanol. A variation of this pathway is to use landfill gas, produced from municipal waste, as the feedstock for methanol synthesis. **Enerkem**, based in Canada, is producing methanol from municipal solid waste (MSW). Rather than being a transportation fuel, the methanol is currently an intermediate product for ultimate production of renewable ethanol and chemicals.⁶

Industrial Waste to Renewable Methanol

In the industrial waste pathway, byproducts and waste products from industrial processes are used as the feedstock for methanol production. As in the municipal waste pathway, the feedstock is gasified to produce syngas for catalytic conversion to methanol. **BioMCN** is currently producing approximately 66 million gallons (250 million liters) per year of renewable methanol⁷ in the Netherlands, using glycerin as the feedstock. This renewable methanol process is synergistic with biodiesel production: the transesterification process of biodiesel production uses methanol, and the byproduct glycerin is then used to produce methanol. In Sweden, **Chemrec** has built and is operating the world's first plant to produce bio-dimethyl ether (DME),⁸ a fuel similar to propane, and renewable methanol is produced in an intermediate step to bioDME production. The process relies on gasification of black liquor, a byproduct of pulp and paper mills. At the demonstration scale, the plant has an annual capacity of 140,000 tons of renewable methanol,⁹ equivalent to 47 million gallons (180 million liters) per year.

Biomass to Renewable Methanol (Biomethanol)

In the biomass pathway, biomethanol is produced from biomass feedstocks, such as agricultural residues, forest trimmings, and short rotation crops. The biomass undergoes gasification into syngas and is subsequently converted into renewable methanol using a catalyst.

VärmlandsMetanol is planning to build a biomethanol plant in Sweden that uses forest biomass

⁶ Enerkem. "Process." <http://enerkem.com/en/technology-platform/process.html>. Accessed September 2012.

⁷ Arden, W. "Introduction to Renewable Methanol: How the U.S. Can Lessen Dependence on Petroleum." Presented to the staff of Senators Daniel Kahikina Akaka (Hawaii) and John Hoeven (North Dakota). April 14, 2011.

⁸ Chemrec. "Report from the Bio-DME Plant in Piteå." <http://www.chemrec.se/Report-from-the-Bio-DME-plant-in-Pite%C3%A5.aspx>. May 2012.

⁹ Salomonsson, P. "BioDME: From Wood to Wheel." BioDME presentation at 7th Asian DME Conference, Niigata, Japan. November 16, 2011.

residue as its feedstock. The planned capacity of this facility is 34 million gallons (130 million liters) per year.¹⁰

CO₂ to Renewable Methanol

Unlike the three pathways above where feedstocks are first broken down then converted into methanol, the CO₂ pathway creates methanol from CO₂ and water building blocks. CO₂ can be sourced from flue streams, captured CO₂, or CO₂ that would otherwise be vented. Using electricity generated from renewable sources (e.g., solar, hydro, wind, and geothermal energy), water is split into hydrogen and oxygen via electrolysis. Renewable methanol is then synthesized from the hydrogen and CO₂. **Carbon Recycling International (CRI)** operates a renewable methanol plant in Iceland with a production capacity of 1.3 million gallons per year (5 million liters per year), and future commercial plants are planned for 13 million gallons (50 million liters) per year of renewable methanol.¹¹ The process currently uses geothermal CO₂ emissions but is designed to also be able to use industrial CO₂ sources. In Canada, the technology used by **Blue Fuel Energy** can produce methanol or process it further into DME or gasoline.¹² CO₂ is captured from industrial sources and combined catalytically with hydrogen formed by electrolyzers powered by renewable electricity. The planned capacity of Blue Fuel Energy's first plant is approximately 150 million gallons (570 million liters) per year.¹³

Other Pathways

Additional variations of the above pathways exist, and other producers have expressed interest in renewable methanol. In the U.S., the **University of California Riverside** proposed the Hynol process, where biomass and hydrogen are combined at high pressure and temperature to generate syngas for methanol synthesis. The waste gas and heat from the process are recycled back into the Hynol reactor for further gasification of biomass.¹⁴ At **Los Alamos National Laboratory**, the Green Freedom™ process captures and recovers CO₂ from the atmosphere to combine with hydrogen derived from electrolysis to create synthetic fuels and chemicals.¹⁵ **Syntec Biofuel** is developing and commercializing a technology to convert waste cellulosic biomass into ethanol and other alcohol fuels via a gasification process.¹⁶ **Gas Technologies** relies on a proprietary reactor and scrubber process to create methanol, formaldehyde, and ethanol directly from methane, without an intermediate syngas step.¹⁷ **Range Fuels** developed a thermochemical process to produce cellulosic ethanol, methanol, and higher alcohols using biomass, but its

¹⁰ VärmlandsMetanol. "In Short About VärmlandsMetanol AB." January 2012.

¹¹ Carbon Recycling International. "Plants." http://www.carbonrecycling.is/index.php?option=com_content&view=article&id=6&Itemid=19&lang=en. Accessed September 2012.

¹² Blue Fuel Energy. "The Case for Renewable Methanol and Gasoline." January 2011.

¹³ Blue Fuel Energy. "Blue Fuel Production." <http://bluefuelenergy.com/blue-fuel-methanol-production/blue-fuel-methanol-production.html>. Accessed September 2012.

¹⁴ Norbeck, J.M., K. Johnson. "The Hynol Process: A Promising Pathway for Renewable Production of Methanol." University of California Riverside, College of Engineering, Center for Environmental Research and Technology. October 2000.

¹⁵ Martin, F.J., W.L. Kubic. "Green Freedom™: A Concept for Producing Carbon-Neutral Synthetic Fuels and Chemicals (Patent Pending)." Los Alamos National Laboratory, LA-UR-07-7897. November 2007.

¹⁶ Syntec Biofuel. "Technology." <http://www.syntecbiofuel.com/process.php>. Accessed September 2012.

¹⁷ Gas Technologies LLC. "The GasTechno® Process." <http://www.gastechno.com/gastechno-process-technology.html>. Accessed November 2012.

facility was closed in 2011 and purchased by LanzaTech, which has indicated that it does not produce methanol. In Canada, **Air Fuel Synthesis** is producing methanol at the demonstration scale from CO₂ captured from the atmosphere.¹⁸ The company indicates that its electrolysis process could be powered using renewable energy to produce renewable methanol. In Japan, **Mitsui Chemicals** previously announced plans to produce renewable methanol from CO₂ in a pilot facility,¹⁹ but the company has also indicated that it does not produce renewable methanol. In Qatar, **Mitsubishi Heavy Industries** has been contracted to build a CO₂ recovery plant to increase methanol production at **Qatar Fuel Additives Company's** methanol production facility.²⁰

¹⁸ Air Fuel Synthesis. "Lotus Exige 270E Tri-Fuel." <http://www.airfuelsynthesis.com/investment-opportunity/projects/lotus-exige-270e-tri-fuel-.html>. Accessed September 2012.

¹⁹ Mitsui Chemicals. "Mitsui Chemicals to Establish a Pilot Facility to Study a Methanol Synthesis Process from CO₂." Press release. August 25, 2008.

²⁰ Mitsubishi Heavy Industries. "MHI Receives Large-Scale CO₂ Recovery Plant Order from Petrochemical Company in Qatar, for Increased Methanol Production." <http://www.mhi.co.jp/en/news/story/1203151511.html>. March 15, 2012.

3 Renewable Methanol Pathway Emissions

A key benefit of renewable methanol is its potential to significantly reduce GHG emissions from the transportation sector. For transportation fuels, GHG emissions are evaluated on a full fuel cycle, or “well-to-wheels” (WTW), basis, taking into account all emission events from feedstock to fuel production to vehicle use. The full fuel cycle is further divided into the “well-to-tank” (WTT) portion and the “tank-to-wheels” (TTW) portion.

As presented in Table 1, relative to conventional fuels on a WTT basis, producers estimate that renewable methanol offers carbon reduction benefits ranging from 65 percent (corresponding to methanol produced from average British Columbia grid electricity) to 95 percent (corresponding to methanol produced from gasification of black liquor). These GHG benefits are among the highest for alternative fuels that can displace gasoline and diesel. For comparison, carbon reduction benefits for a sample of these other alternative fuels are shown in Table 2 (a negative value indicates that the alternative fuel has higher WTT GHG emissions than the conventional fuel). As with other alternative fuels that use waste carbon as their feedstocks, the carbon inputs for renewable methanol must be appropriately credited when estimating WTT emissions. Methanol pathways using industrial or geothermal carbon dioxide streams that would otherwise be emitted to the atmosphere can be considered carbon neutral for the feedstock fraction of their full fuel cycle emissions; however, the use of waste carbon is not carbon negative (i.e., sequestration), because eventual use of the fuel in the vehicle releases the feedstocks’ carbon.

Table 1. Carbon Reduction Benefits for Renewable Methanol

Renewable Methanol Producer	Reported Carbon Reduction Relative to Conventional Fuel (%)
BioMCN ²¹	78
Blue Fuel Energy ²²	65 to 84
Carbon Recycling International ²³	85
Chemrec ²⁴	95
VärmlandsMetanol ²⁵	80 to 90

²¹ Ryan, M. “Methanol and Fuel Cells: Renewable Methanol.” FuelCellToday. <http://www.fuelcelltoday.com/analysis/analyst-views/2012/12-06-06-methanol-and-fuel-cells-renewable-methanol>. June 6, 2012.

²² Blue Fuel Energy. “Lifecycle Assessment of Blue Fuel Methanol with GHGenius.” <http://bluefuelenergy.com/ghgenius/ghgenius.html>. Accessed September 2012.

²³ Email communication with Omar Sigurbjörnsson, Carbon Recycling International, December 5, 2012.

²⁴ Email communication with Ingvar Landälv, Chemrec, December 12, 2012.

²⁵ VärmlandsMetanol AB. “Uhde Gasification Selected for World’s First Commercial Biomass-to-Methanol Plant for VärmlandsMetanol AB, Hagfors, Sweden.” Press release. July 23, 2010.

Table 2. Carbon Reduction Benefits for Other Alternative Fuels²⁶

Alternative Fuel	Carbon Reduction Relative to Conventional Fuel (%)	Notes
Biodiesel	84	Conversion of used cooking oil to fatty acid methyl esters where "cooking" is required
Compressed natural gas from landfill gas	89	Cleaned up to pipeline quality natural gas, compressed in California
Compressed natural gas from pipeline	31	North American, delivered via pipeline, compressed in California
Electricity	-6 to -7	California marginal mix of natural gas and renewable energy sources
Ethanol from corn	-0.2	Midwest average, 80% dry mill, 20% wet mill, dry distillers grains with solubles, natural gas
Ethanol from sugarcane	26	Brazilian sugarcane using average production processes
Hydrogen	22 to 23	Compressed, from on-site reforming with renewable feedstocks
Liquefied natural gas	15 to 16	North American, delivered via pipeline, liquefied using liquefaction with 80% efficiency

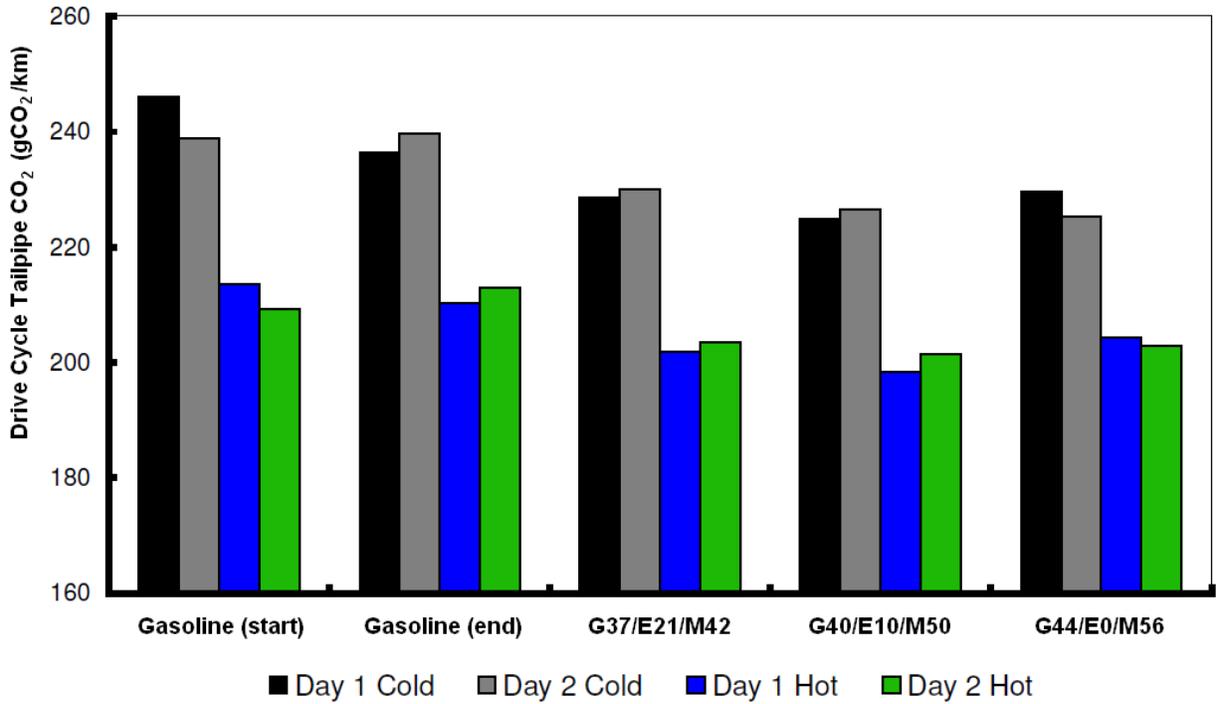
For the TTW portion of the full fuel cycle, methanol as a transportation fuel can offer two types of advantages over conventional fuels: lower tailpipe emissions in combustion and higher efficiency vehicle technologies. When used to fuel a combustion engine, methanol has been shown to emit less carbon than gasoline. In a study of tri-fuel blends containing varying levels of methanol, ethanol, and gasoline, alcohol fuel blends show approximately 15 to 20 percent reduction in carbon emissions than pure gasoline (Figure 1).²⁷ As an alternative to combustion, methanol can also be used in fuel cells, an advanced vehicle technology where the fuel is used to generate electricity for motive power. Proton exchange membrane fuel cells are estimated to be 2.6 to 3.5 times more efficient than combustion engines;²⁸ when fuel consumption is reduced, resulting tailpipe emissions are reduced as well.

Together, the WTT and TTW GHG emissions of renewable methanol represent compelling benefits that can enable the transportation sector to meet ambitious carbon reduction goals.

²⁶ Calculated from California Air Resources Board "Low Carbon Fuel Standard Final Regulation Order," October 11, 2012.

²⁷ Turner, J.W.G., R.J. Pearson, M.A. McGregor, J.M. Ramsay, E. Dekker, B. Iosefa, G.A. Dolan, K. Johansson, K. ac Bergström. "GEM Ternary Blends: Testing Iso-Stoichiometric Mixtures of Gasoline, Ethanol and Methanol in a Production Flex-Fuel Vehicle Fitted with a Physical Alcohol Sensor." SAE Technial Paper 2012-01-1279. 2012.

²⁸ Methanol Fuel Cell Alliance. "Joint Position Document." September 15, 2002.



(Alcohol fuel blends are expressed as percentages of gasoline (G), ethanol (E), and methanol (M), respectively.)

Figure 1. Tailpipe Carbon Emissions of Gasoline and Alcohol Fuel Blends²⁹

²⁹ Figure adapted from Turner, J.W.G., R.J. Pearson, M.A. McGregor, J.M. Ramsay, E. Dekker, B. Iosefa, G.A. Dolan, K. Johansson, K. ac Bergström, "GEM Ternary Blends: Testing Iso-Stoichiometric Mixtures of Gasoline, Ethanol and Methanol in a Production Flex-Fuel Vehicle Fitted with a Physical Alcohol Sensor," SAE Technial Paper 2012-01-1279, 2012.

4 Market Dynamics

The expansion of renewable methanol, while not currently a significant player in the transportation fuel market, may be encouraged and influenced by several key drivers: 1) renewable feedstock availability, 2) production of renewable methanol, 3) economics, 4) policies and regulations, and 5) fuel applications and derivative markets. These drivers are discussed below.

Renewable Feedstock Availability

Feedstock availability is not expected to present barriers to renewable methanol production. The primary pathways for producing renewable methanol all rely on waste feedstocks—waste biomass, municipal waste, industrial waste, industrial emissions, and existing sources of CO₂—and these feedstocks generally scale with global energy and resource demand. In the U.S. alone, the total potential biomass resource for biofuels is estimated to be as much as 1.6 billion dry tons per year by 2030.³⁰ Using mature gasification technology,³¹ this biomass resource is equivalent to 264 billion gallons per year of methanol. (For comparison, U.S. sales of gasoline in 2011 totaled 130 billion gallons.³²) It is important to note, however, that while renewable feedstocks are not likely to be the main limiting factor for methanol production, methanol will need to compete with other renewable fuels, such as ethanol, renewable gasoline, biodiesel, and renewable natural gas, for feedstock supplies. Renewable methanol has an advantage among alternative fuels in that it is one of few fuels actively seeking to use CO₂ streams as its feedstock.

Production of Renewable Methanol

Because methanol and its derivatives are already well established in the global chemicals market (and to some extent in the transportation market as well), the infrastructure and logistics for distributing the produced renewable methanol are not expected to present a significant challenge. Over ninety methanol plants worldwide currently offer a combined capacity of nearly 24 billion gallons (90 billion liters) per year,³³ and thus renewable methanol can leverage this industry knowledge base. Commercial-scale production of the renewable methanol for transportation and power generation will depend on the success of the key producers in scaling up their operations, which presently range from 1.3 to 150 million gallons (5 to 570 million liters) per year. The proof-of-concept and demonstration projects that are underway today will pave the road to renewable methanol's viability as an alternative fuel, and progress is continuing to be made.

Economics

The economic viability of renewable methanol will depend largely on how its price compares to that of methanol produced from fossil fuels and that of competing transportation fuels, both

³⁰ Perlack, R.D., B.J. Stokes. "U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry." Prepared by Oak Ridge National Laboratory for the U.S. Department of Energy. ORNL/TM-2011/224. August 2011.

³¹ Corresponding to a conversion yield of 165 gallons of methanol per 1 dry ton of biomass.

³² U.S. Energy Information Administration. "Petroleum & Other Liquids: Prices, Sales Volumes & Stocks by State." http://www.eia.gov/dnav/pet/pet_sum_mkt_dcu_nus_a.htm. Accessed November 2012.

³³ Methanol Institute. "The Methanol Industry." <http://methanol.org/Methanol-Basics/The-Methanol-Industry.aspx>. Accessed September 2012.

conventional and alternative. Future demands for methanol products and for fuels will determine the price dynamics between renewable methanol and its competitors. In the global environment of high oil prices and relatively low natural gas prices projected by the U.S. Energy Information Administration over the next two decades,³⁴ methanol produced from natural gas may be an increasingly attractive transportation fuel option. Depending on how renewable methanol production scales during this period, there may be opportunities for natural gas methanol and renewable methanol to grow synergistically.

The cost of producing methanol from natural gas is estimated to range from \$1.30 to \$1.60 per gasoline gallon equivalent when natural gas is \$4 to \$6 per MMBtu.³⁵ While renewable methanol production costs at its present stages of commercialization are higher than those of fossil fuels, they are “very competitive against bioethanol”³⁶ and are expected to offer a lower cost way to meet the targets of renewable fuel mandates, such as the European Union (EU)’s Renewable Energy Directive, than other renewable fuel blends.³⁷ As renewable methanol production scales up and petroleum prices rise due to growing global demand, the economics of renewable methanol as an alternative fuel will become increasingly attractive. Furthermore, regulations that constrain carbon emissions, such as cap-and-trade systems and the EU Emissions Trading System, create opportunities for renewable fuels to benefit economically from carbon credits. Renewable methanol producers have indicated that they are positioned to “derive revenues from the carbon credit and renewable fuel markets.”³⁸

The renewable methanol pathways being pursued today rely on feedstocks that have little value or would otherwise incur fees for their generators, which is advantageous for the economics of renewable methanol. For municipal waste, landfill tipping fees are required for disposal of the waste, and thus renewable methanol producers are able to obtain these feedstocks for zero or negative cost (i.e., municipal waste generators pay renewable methanol producers to take the waste). Similarly, many industrial emitters of CO₂ are currently limited in the amount of carbon they may release into the atmosphere or expect to be so regulated in the near future. Industrial producers of low-value byproducts and producers of biomass waste seek ways to add value to their products, and serving the transportation fuel market through renewable methanol production provides one option. However, by general principles of supply and demand, zero and negative waste feedstock costs are unlikely to persist in the long term if renewable fuels are able to scale up successfully. As such, the minimization of other renewable methanol cost components, including feedstock transportation, conversion, distribution, storage, and retail costs, will be essential for market competitiveness.

³⁴ U.S. Energy Information Administration. “Annual Energy Outlook 2012.” June 2012.

³⁵ Cohn, D.R. “Natural Gas for Transportation: Prospects for Security and Environmental Benefits.” Environmental and Energy Study Institute Congressional Briefing. March 16, 2011.

³⁶ Just-Auto. “Q&A with BioMCMN – Rob Voncken, CEO.” http://www.just-auto.com/interview/qa-with-biomcn-rob-voncken-ceo_id101248.aspx. September 22, 2009.

³⁷ BioMCN. “Bio-Methanol Blends.” <http://www.biomcn.eu/our-product/applications/30-bio-methanol-blends.html>. Accessed September 2012.

³⁸ Carbon Recycling International. “First Commercial Plant.” http://www.carbonrecycling.is/index.php?option=com_content&view=article&id=14&Itemid=8&lang=en. Accessed September 2012.

Policies and Regulations

In addition to potential fuel cost savings, the market for renewable methanol is driven by policies and regulations. As countries around the world impose caps on carbon emissions, mandate the use of renewable fuels, and establish policies for greater energy security, renewable methanol offers one option for compliance. Though the renewable fuels market to date has been dominated by ethanol and biodiesel, efforts are underway to develop additional advanced biofuels. In the framework of current and future policies, methanol will need to compete with these renewable fuels for market share.

The focus of relevant policies and regulations is on GHG emissions and the reductions offered by renewable fuels compared to conventional fuels. As discussed above, the emissions benefits of renewable methanol may be as much as 95 percent GHG reduction relative to conventional fuel, placing it among the renewable fuels with the very lowest carbon intensities.³⁹ As renewable methanol's full fuel cycle emissions are fully verified and accepted by relevant governing bodies, it can be used to meet major renewable fuel regulations around the world (Table 3). Other general policies, such as Iceland's goal for a carbon-neutral economy and the Kyoto Protocol, also support the market adoption of fuels such as renewable methanol. In Sweden, favorable taxes specifically for renewable methanol further encourage its use.⁴⁰

Table 3. Major Renewable Fuel Regulations

Regulation Type	Applicable Regions
Renewable fuel standard	<ul style="list-style-type: none"> • Canada: Federal Renewable Fuels Regulation • EU: Directive 2009/28/EC (Renewable Energy Directive) • U.S.: Renewable Fuel Standard
Low carbon fuel standard	<ul style="list-style-type: none"> • Canada (British Columbia): Renewable & Low Carbon Fuel Requirements Regulation • EU: Directive 2009/30/EC (Fuel Quality Directive) • U.S. (California): Low Carbon Fuel Standard (also being considered in Oregon, Washington, the Northeast and Mid-Atlantic states, the Midwest states, and at the national level)
Renewable portfolio standard	<ul style="list-style-type: none"> • China • EU (Belgium, Britain, Germany, Italy, Sweden) • U.S. (36 states and District of Columbia)

In order for renewable methanol to be integrated into the existing transportation fuel market, additional regulations must be considered. Existing rules regarding fuels and fuel blends dictate whether methanol can be incorporated; the EU and the U.S. are two notable examples. In the EU,

³⁹ Compared to other fuel pathways in the California Air Resources Board Low Carbon Fuel Standard Final Regulation Order, October 11, 2012.

⁴⁰ Terland, O. "Rottneros." Presentation to SEB Enskilda. September 28, 2011.

gasoline specification EN 228 allows up to 3 percent methanol in gasoline with cosolvents, and this allowance is being used in limited markets in some EU member states. In the U.S., methanol received a waiver from the Clean Air Act that allows it to be blended into gasoline at 5 percent with cosolvents. However, this waiver cannot be used with the waiver allowing 10 percent ethanol blends. Thus, the current use of ethanol in gasoline to meet the Renewable Fuel Standard (RFS2) competes with the use of methanol under RFS2. To enable a demand for methanol, the proposed Open Fuel Standard Act would require new cars to have flexible tri-fuel capability (methanol, ethanol, and/or gasoline) that ensures that vehicle emissions with the use of methanol can be acceptable under the Clean Air Act. The Lotus tri-fuel Exige 270E is one example of a vehicle designed to operate on any combination of gasoline, ethanol, and methanol,⁴¹ although studies to date have indicated that existing flex-fuel vehicles (designed to operate on E85) are already able to use tri-fuel blends with essentially no difference in performance.⁴² In addition, the U.S. Environmental Protection Agency's recent decisions to approve the use of two alternative corrosion inhibitors, TOLAD MFA-10A and TXCeed, in Texas Methanol Corporation's gasoline-alcohol fuel, OCTAMIX,⁴³ reflects continued interest in the use of methanol as a transportation fuel.

Methanol Applications and Derivative Markets

Methanol serves three key markets: chemicals, transportation, and power generation. The dynamics of renewable methanol in each of these markets will depend on their respective demand and prices. Market segments that offer an advantage for renewably-produced methanol, such as transportation and electricity generation, are more likely to see renewable methanol use, whereas market segments in which no such advantages are offered are expected to use the least expensive form of methanol, likely produced from natural gas or coal.

An estimated total of 49.8 million tons (45.20 million metric tonnes) of methanol and its derivatives are used annually in the world (Figure 2),⁴⁴ and China is on track to become the world's leading methanol market.⁴⁵ The chemicals market represents the biggest demand for methanol in the world today. This market encompasses methanol and its many derivatives, including: acetic acid, dimethyl terephthalate, formaldehyde, methanethiol, methanol-to-olefins, methyl chloride, methyl methacrylate, methyl tert-butyl ether (MTBE), and methylamines.⁴⁶

⁴¹ Brueckner, S., R.J. Pearson, J.W.G. Turner. "Sustainable Organic Fuels for Transport – SOFT." Lotus Engineering. January 2011.

⁴² Turner, J.W.G., R.J. Pearson, M.A. McGregor, J.M. Ramsay, E. Dekker, B. Iosefa, G.A. Dolan, K. Johansson, K. ac Bergström. "GEM Ternary Blends: Testing Iso-Stoichiometric Mixtures of Gasoline, Ethanol and Methanol in a Production Flex-Fuel Vehicle Fitted with a Physical Alcohol Sensor." SAE Technial Paper 2012-01-1279. 2012.

⁴³ U.S. Environmental Protection Agency. "EPA Announces Decision for Regulation of Fuel and Fuel Additives: Modification to Octamix Waiver Regarding TXCeed." EPA-420-F-12-020. <http://www.epa.gov/oms/fuels/registrationfuels/documents/420f12020.pdf>. June 2012.

⁴⁴ MMSA. "Global Supply and Demand." <http://www.methanol.org/Methanol-Basics/Resources/MMSA-Global-Methanol-Supply-and-Demand.aspx>. Accessed September 2012.

⁴⁵ Stephan, D. "China and Middle East Compete for Leadership in Methanol." *Process Worldwide*. http://www.process-worldwide.com/engineering_construction/materials/specialities/articles/360576/. April 13, 2012.

⁴⁶ MMSA. "Global Supply and Demand." <http://www.methanol.org/Methanol-Basics/Resources/MMSA-Global-Methanol-Supply-and-Demand.aspx>. Accessed September 2012.

These methanol derivatives are subsequently used to produce a wide variety of everyday products, ranging from plastics to windshield fluid.⁴⁷

In addition, methanol, particularly renewable methanol, can play a number of roles in the transportation and power generation markets. Nearly 25 percent of worldwide demand for methanol is estimated to come from applications in the energy sector.⁴⁸ Fuel cell applications span both the transportation and power generation markets, ranging from fuel cell vehicles to stationary generators. For example, Wärtsilä methanol fuel cells are being used to power commercial ships.⁴⁹ Methanol can be used as the hydrogen carrier for fueling fuel cells and offers the advantage of being more easily transported than gaseous hydrogen. Because fuel cell use is often driven by renewable fuel and power generation standards, renewable methanol can be effective in these markets. In transportation, methanol can be used as a neat fuel, blended into gasoline, or converted to DME as a diesel fuel replacement. China is one primary market for methanol as a transportation fuel, where low-cost coal feedstocks enable the production of relatively inexpensive methanol fuel as an attractive alternative to conventional fuels. In Europe, testing is currently underway for Volvo DME-fueled trucks as part of the EU's BioDME project.⁵⁰ In addition, methanol is currently used in the production of biodiesel, making methanol a versatile product that can be used as an alternative fuel, a renewable fuel, and a precursor to other alternative and renewable fuels. One notable methanol derivative relevant to the transportation market is MTBE. While its use as a gasoline oxygenate has been deselected in the U.S. because of groundwater contamination concerns and its substitution by ethanol, MTBE continues to be used in other countries around the world to improve gasoline engine performance.

⁴⁷ Methanol Institute. "Applications for Methanol." <http://www.methanol.org/Methanol-Basics/Methanol-Applications.aspx>. Accessed September 2012.

⁴⁸ Stephan, D. "China and Middle East Compete for Leadership in Methanol." *Process Worldwide*. http://www.process-worldwide.com/engineering_construction/materials/specialities/articles/360576/. April 13, 2012.

⁴⁹ "EU Gives €1M Grant to Fund On-Board Fuel Cell Project." *ICIS Chemical Business*, p. 40. December 18, 2006-January 7, 2007.

⁵⁰ Chemrec. "Kick-Off: CHEMREC to Build World's First BioDME Advanced Biofuels Plant." Press release. September 8, 2008.

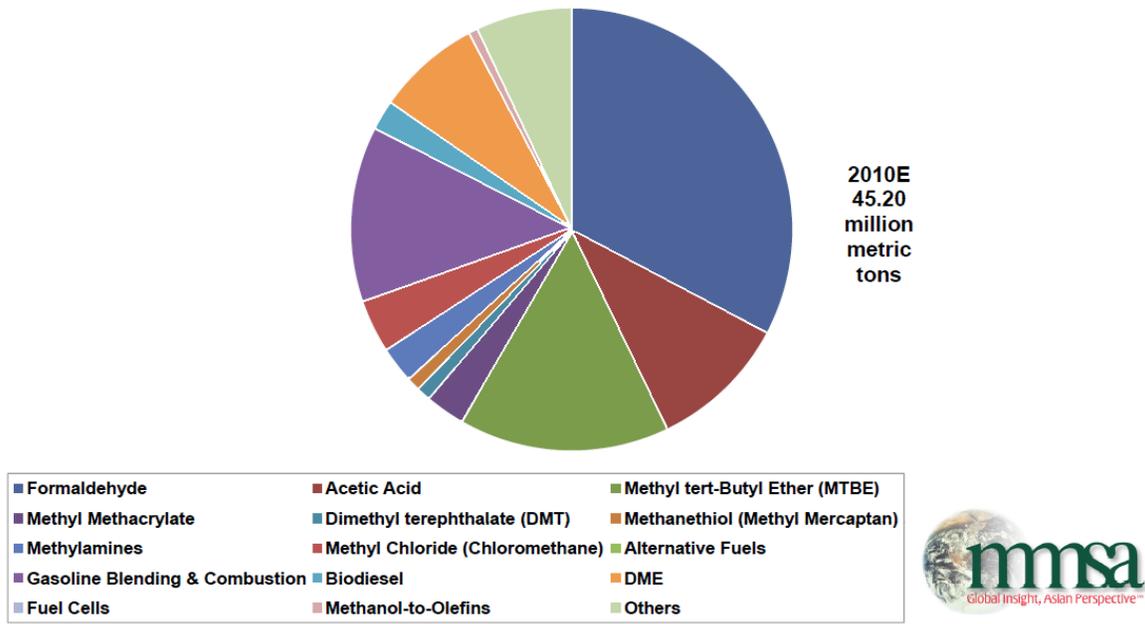


Figure 2. Worldwide Use of Methanol and Its Derivatives⁵¹

⁵¹ Figure adapted from MMSA, “Global Supply and Demand,” <http://www.methanol.org/Methanol-Basics/Resources/MMSA-Global-Methanol-Supply-and-Demand.aspx>, accessed September 2012.

5 Case Studies

Discussions of three renewable methanol producers are presented below. The selection of these producers as examples is not intended to be endorsements of their processes or judgments regarding their viability. Instead, these brief case studies are intended to highlight major considerations and key lessons for growing the renewable methanol industry.

BioMCN

BioMCN, based in the Netherlands, is the world's largest producer of second generation biofuels.⁵² As the first producer to sell industrial quantities of renewable methanol,⁵³ BioMCN illustrates the value of partnerships and consideration of the entire supply chain to the company's success. These elements of its business plan increase its likelihood of long-term commercial viability.

Founded in 2006, BioMCN produces approximately 66 million gallons (250 million liters) per year of renewable methanol⁵⁴ using waste glycerin from biodiesel production. Much of this methanol is sold into the transportation market for gasoline blending, which can help meet Renewable Energy Directive targets for the EU. For greater feedstock flexibility, BioMCN is currently expanding its capabilities to produce methanol from woody biomass feedstocks as well. The company purchased existing plants that produced methanol from natural gas, and retrofits are underway for production of woody biomass methanol, with the goal of an operational project by 2015.⁵⁵ Between 2011 and 2012, BioMCN secured partners at both ends of the supply chain. It signed an agreement with ED&F Man for the souring and delivery of biodiesel byproduct glycerin from Argentina, one of world's top biodiesel-producing countries, thereby ensuring its supply of renewable feedstock and expanding its business scope to Latin America.⁵⁶ BioMCN also signed agreements with Vertis Environmental Finance and Nordic Green for sales of renewable methanol in Europe and representation worldwide for fuel cell applications.⁵⁷ In 2012, the consortium formed by BioMCN, Siemens, Linde, and Visser & Smit Hanab received €199

⁵² BioMCN. "Driven to Produce Bio-Methanol." <http://www.biomcn.eu/about-us/our-vision.html>. Accessed September 2012.

⁵³ BioMCN. "Driven by Nature." <http://www.biomcn.eu/>. Accessed September 2012.

⁵⁴ Arden, W. "Introduction to Renewable Methanol: How the U.S. Can Lessen Dependence on Petroleum." Presented to the staff of Senators Daniel Kahikina Akaka (Hawaii) and John Hoeven (North Dakota). April 14, 2011.

⁵⁵ Voegelé, E. "BioMCN Aims to Develop Wood-to-Methanol Plant in Netherlands." *Biodiesel Magazine*. <http://www.biodieselmagazine.com/articles/7820/biomcn-aims-to-develop-wood-to-methanol-plant-in-netherlands>. May 27, 2011.

⁵⁶ Voegelé, E. "BioMCN, ED&F Man Sign Supply Deal for Argentine Glycerin." <http://www.biodieselmagazine.com/articles/8433/biomcn-edf-man-sign-supply-deal-for-argentine-glycerin>. April 12, 2012.

⁵⁷ Biofuels Digest. "BioMCN Signs Vertis, Nordic Green for Sales of Biomethanol." <http://www.biofuelsdigest.com/bdigest/2011/12/22/biomcn-signs-vertis-nordic-green-for-sales-of-biomethanol/>. December 22, 2011.

million (\$264 million) in European Commission grants for its Woodspirit project to construct a large-scale biomass refinery.⁵⁸

BioMCN's activities to date reflect successful partnerships that provide the framework for its methanol production. As renewable methanol producers scale their operations from demonstrations to commercial production, consideration of pivotal elements along the supply chain will be crucial.

Range Fuels

Range Fuels, a U.S. company, is an example of some of the technical and financial challenges facing renewable fuel producers. In particular, overly aggressive timelines for scale-up of operations, technical difficulties in feedstock processing and fuel production, and lack of clear communication about intended products may lead to misaligned expectations.

Range Fuels developed a process for producing alcohol fuels from gasification of wood chips. Seeking funding for the production of cellulosic ethanol, it received the United States Department of Agriculture (USDA)'s first biofuels loan guarantee of \$64 million, with additional funding from the United States Department of Energy (DOE) and others.⁵⁹ In 2007, the company began construction on its facility in Soperton, Georgia, with a planned production of 20 million gallons (76 million liters) of biofuel per year by 2008 and over 100 million gallons (379 million liters) by 2009.⁶⁰ Once the plant came online, Range Fuels began producing methanol. However, the company encountered technical challenges with its wood processing section and its shift to producing ethanol. Because its agreements with USDA and DOE were contingent upon production of certain levels of cellulosic ethanol, Range Fuels was forced to liquidate its assets by the government when it failed to produce sufficient quantities of fuel.⁶¹ Its assets were purchased in 2012 by LanzaTech, a New Zealand company, for \$5.1 million, and the facility will be used to produce ethanol from wood chips, using a process different from that of Range Fuels.⁶²

Fundamentally, the example provided by Range Fuels does not suggest that renewable methanol is not viable. Instead, it reflects the difficulties faced by new fuels in growing to scale. Technical issues are expected for the start-up of any fuel production operation, and investor expectations must be reasonably managed. Like many renewable fuel technologies, multiple fuel products are technically possible. Confusion about which of the possible products would be produced and challenges in actually producing those products contributed to Range Fuels' difficulties.

⁵⁸ BioMCN. "Brussels Grants a 199 Million Euros Subsidy to Dutch Biomass Refinery Initiative." <http://www.biomcn.eu/news/news/158-brussels-grants-a-199-million-euros-subsidy-to-dutch-biomass-refinery-initiative.html>. December 18, 2012.

⁵⁹ Biofuels Digest. "The Range Fuels Failure." <http://www.biofuelsdigest.com/bdigest/2011/12/05/the-range-fuels-failure/>. December 5, 2011.

⁶⁰ Parker, M. "Range Fuels Cellulosic Ethanol Plant Fails, U.S. Pulls Plug." Bloomberg. <http://www.bloomberg.com/news/2011-12-02/range-fuels-cellulosic-ethanol-plant-fails-as-u-s-pulls-plug.html>. December 2, 2011.

⁶¹ *Ibid.*

⁶² Duncan, S.H. "Shattered Range Fuels Plant Prepares for New Life." The Telegraph. <http://www.macon.com/2012/02/18/1910288/shattered-range-fuels-plant-prepares.html>. February 18, 2012.

Renewable methanol has an advantage over other biofuels in that wood methanol production is an established process. However, as demonstrated by Range Fuels, expanding the scale of production in today's transportation market necessarily entails risks and challenges.

Carbon Recycling International

CRI was founded in 2006 in Iceland and represents a targeted venture to produce methanol renewably from CO₂ and renewable electricity. By focusing initially on a specific market entry strategy and setting modest scale-up goals, this producer is poised to develop a renewable methanol production system that can be replicated in various sites around the world.

CRI's first commercial plant was completed in 2011. The plant produces 0.5 million gallons (2 million liters) per year of renewable methanol, with plans to expand to 1.3 million gallons (5 million liters) per year by 2012.⁶³ Like BioMCN, CRI's product is intended to be blended into gasoline to serve the European markets where renewable methanol is accepted as a renewable fuel under the Renewable Energy Directive. The current plant uses geothermal CO₂ emissions as its feedstock but is able to also use industrial CO₂ sources. The company relies on a modular facility design, where components are built in various different locations then rapidly assembled and integrated at the production site.⁶⁴ CRI plans to construct a larger facility in Iceland to produce up to 13 million gallons (50 million liters) per year for export to other European countries and to establish the feasibility of its commercial scale modular design for deployment in other locations.⁶⁵

CO₂ emissions and employing stranded renewable energy assets. The blending of its product into gasoline helps address issues regarding its acceptability in the existing transportation market. By scaling modestly in its first production facility, the company improves its likelihood of success against expectations. If CRI is able to establish its larger modular facility and meet production goals, it will open up opportunities elsewhere in the world where renewable energy resources and larger sources of CO₂ emissions are co-located.

⁶³ Carbon Recycling International. "First Commercial Plant." http://www.cri.is/index.php?option=com_content&view=article&id=14&Itemid=8&lang=en. Accessed September 2012.

⁶⁴ Harris, S. "Chemical Potential: Turning Carbon Dioxide into Fuel." *The Engineer*. <http://www.theengineer.co.uk/sectors/energy-and-environment/in-depth/chemical-potential-turning-carbon-dioxide-into-fuel/1013459.article>. August 9, 2012.

⁶⁵ Carbon Recycling International. "First Commercial Plant." http://www.cri.is/index.php?option=com_content&view=article&id=14&Itemid=8&lang=en. Accessed September 2012.

6 Conclusions

Compared to other transportation fuels, there are currently few renewable methanol companies, and worldwide production of renewable methanol for the transportation and power generation markets is low. However, these companies are demonstrating that renewable methanol is a viable alternative fuel option that merits further exploration and development in today's regulatory climate. Market adoption will be largely dictated by: 1) the production volumes that can be attained commercially; 2) its economics relative to conventional and other renewable fuels; 3) policies supporting or hindering renewable methanol as a fuel; and 4) demand from other methanol applications and derivative markets. The most promising efforts are still underway, and the renewable methanol industry is expected to encounter important decision points and milestones over the next several years.