Methanol for Power Generation: A White Paper

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ENERGY INSIGHT AND CONSULTING

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1.0 EXECUTIVE SUMMARY

- ADI Analytics has developed this white paper to assess the potential of using methanol for power generation. Key goals are to (1) evaluate technical feasibility, (2) assess benefits, costs and economics, and (3) review commercial case studies.

- Methanol's application as a fuel for power generation is becoming more attractive for several reasons. It is cleaner-burning than diesel or fuel oil and can help power plants meet increasingly stringent emission regulations. In comparison to fuel oil and diesel, methanol burns at a lower temperature and its use for power generation can reduce NO_x emissions by at least 80%. Also, methanol does not contain sulfur or heavy hydrocarbons thereby precluding SO_x and particulate matter emissions. Finally, complete combustion of methanol creates fewer CO_2 emissions in comparison to fuel oil and diesel.

- Historically, methanol pricing has been correlated with oil and, therefore, diesel pricing. Even so, new methanol plant announcements based on the cheap, abundant supply of natural gas from shale plays may lead to long-term methanol contracts in the U.S. based on Henry Hub natural gas pricing, which is expected to stay low for the long term. Henry Hub-indexed methanol pricing may be more stable than oil-linked methanol prices helping power plant operators diversify away from fuel oil- or diesel-based pricing.

- Methanol is compatible with existing diesel and fuel oil infrastructure. Relative to LNG and the infrastructure needed to transport such fuels, retrofitting a turbine for methanol may have lower capital costs and fewer infrastructure modifications which lead to fuel price savings especially for small- and medium-sized power plants. As a result of the above factors, methanol can become cost competitive with alternative fuels including fuel oil and diesel for generating power in areas isolated from natural gas supply.

- Small and mid-sized power plants are positioned to benefit the most from methanol-to-power due to constraints with the supply and sourcing of natural gas and alternatives such as LNG. In addition, power plants can be retrofitted to use methanol as a fuel more quickly and easily in comparison to LNG and other alternative clean fuels.

- Based on various operational and financial assumptions for a power plant, levelized costs of power produced using methanol are lower in comparison to that from LNG or diesel. Operators interested in using methanol for power generation should carefully develop sourcing strategies with methanol producers who are willing to sign supply contracts where prices can be indexed to globally traded commodities.

- The feasibility of methanol for power generation has been demonstrated through studies and projects by power plant operators and OEMs. Two power plants in Israel and Trinidad and Tobago have successfully used methanol for power generation using gas turbines ranging from approximately 10 to 50 MW in capacity. Operators considering retrofitting their power plants to enable the use of methanol as a fuel should carefully develop plans to address key technical and operational issues including specifying and procuring retrofit equipment, negotiating methanol supply contracts, optimizing fuel unloading and storage systems, and updating safety processes.

- Most major original equipment manufacturers (OEMs) are capable of supplying and retrofitting equipment with the typical guarantees for power plants to operate on methanol although they may need adequate lead times. Many OEMs have also demonstrated feasibility and benefits of methanol for power generation through studies and projects.

- Methanol is also finding applications as a marine fuel helping boats and ships comply with increasingly stringent emissions regulations. A ferry, the *Stena Germanica*, was retrofitted in 2015 and since that time has been able to operate both on methanol and diesel. The 24 MW Wärtsilä engines used on the *Stena Germanica* are similar to those used in power generation providing additional commercial evidence of methanol's feasibility as a fuel for power generation.

2.0 INTRODUCTION

The discovery and rapid development of shale gas and unconventional oil plays has dramatically increased the supply of natural gas in North America. In the U.S., natural gas from shale basins accounted for less than 1% of total natural gas supply in 2005. Today shale plays provide more than 50% of total natural gas production and have significantly lowered natural gas prices in the U.S. For example, the Henry Hub spot price of natural gas decreased from an average of $4.37 per million British thermal units (Btu) in 2010 to $2.52 in 2016.

This growing natural gas resource can be monetized in several ways including conversion to liquefied natural gas (LNG), methanol, or other liquid hydrocarbons. In North America, there has been a lot of interest in monetizing natural gas through LNG and methanol plants. Currently there are six methanol plants in the U.S. totaling a little over 5 million tons per annum (mtpa) of capacity. Approximately a dozen new plants have been announced but only a few are likely to move forward. Collectively, the U.S. is anticipated to shift from a methanol importer to an exporter soon and domestic methanol capacity is likely to reach almost 16 mtpa by 2020.

Given the promise of new, cheap supply and methanol's clean-burning properties, its application as a fuel for power generation could offer several benefits. Methanol is already being used as a fuel in automobiles but additional promising opportunities include using it to (1) produce power and (2) fuel marine vessels. Each of these is described briefly below.

1. **Fuel for power plants:** Methanol use as a fuel has been proven for engines, turbines, and boilers with only minor equipment modifications. As a result, it can be used as a fuel in regions where natural gas supply is depleting, are geographically isolated, face natural gas supply challenges due to geopolitical problems, or need to reduce emissions. For such regions, it may be far more economical to import methanol than to build new natural gas pipelines, LNG import and regasification terminals, or other gas supply infrastructure.

   Reciprocating engines that typically run on fuel oil or diesel to produce power can also use methanol as a fuel. Reciprocating engines are typically used to produce power on islands and remote regions such as the Caribbean and Africa. Such regions often lack natural gas supply and infrastructure, pay a heavy premium for diesel, and are interested in cheaper, lower-carbon alternative fuels.

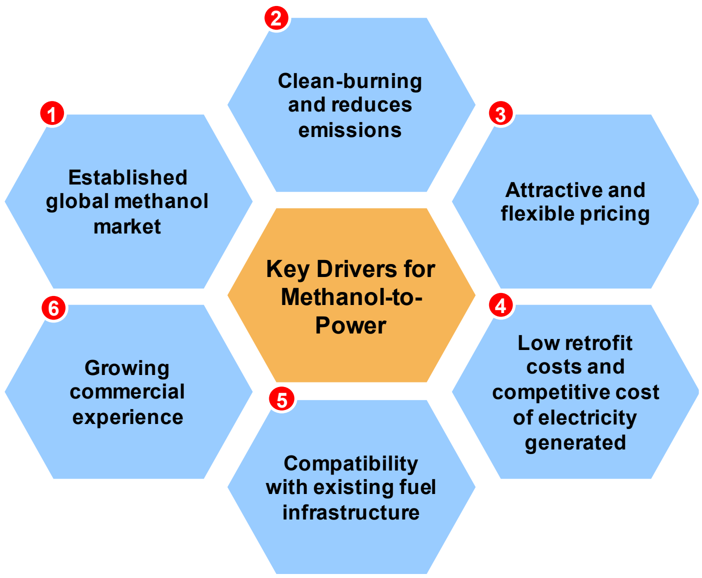
   Power plants smaller than 100 MW in capacity – whether using gas turbines or reciprocating engines – are well positioned to switch to methanol as they would only need small volumes that can be supplied quickly and economically. Methanol use as a fuel requires only minor modifications to gas turbines, reciprocating engines, and boilers, unlike LNG, and may offer higher efficiencies in compression-ignition engines when compared to fuel oil and diesel.

2. **Fuel marine vessels:** Methanol is also being contemplated as a fuel for marine vessels, which require engine modifications and auxiliary system upgrades that are similar to those required for power plants retrofitted to use methanol as a primary fuel. Marine vessels which typically run on heavy fuel oil are now subject to stricter emission regulations set by the International Maritime Organization (IMO) especially in some parts of the world designated as emission control areas (ECA). In order to comply with these regulations, fleet operators are considering switching from heavy fuel oil to low-sulfur diesel, LNG, and methanol. Methanol is a promising marine fuel because it is clean-burning, compatible with existing marine fuel infrastructure, and needs only small engine and infrastructure modifications.

Six factors – see Exhibit 1 – position methanol as an attractive fuel for power generation. First, the methanol market is well established with multiple production plants, global shipping capacity and routes, terminals, and end uses assuring power plant operators of supply security. Second, methanol is a cleaner-burning fuel compared to diesel and can help power plants reduce emissions. Third, methanol pricing can be competitive, flexible with indexation to oil or potentially natural gas, and include price caps and/or floors with variable volumes and tenors. Additionally, methanol can be procured from a wider range of plants in comparison to LNG whose supply contracts are often linked to a specific plant although the share of the spot trade market is growing.

Fourth, methanol-based power can be more competitive economically as capital costs to retrofit power plants to use methanol are lower than those for using LNG, which requires large and expensive LNG regasification facilities. In addition, methanol production costs have been lowered by cheaper natural gas in North America and methanol prices have competed historically with diesel. Fifth, methanol is compatible with existing diesel infrastructure reducing implementation time and cost. Finally, methanol-based power's technical, economic, and environmental viability are growing with commercial projects and OEM research and studies.

Exhibit 1. Six factors position methanol as an attractive fuel for power generation.



This white paper summarizes the methanol market and applications in Section 3, evaluates the environmental benefits of using methanol for power generation in Section 4, and assesses methanol pricing in Section 5. Section 6 focuses on the costs and economics of power produced from methanol followed by an assessment of methanol's compatibility with existing infrastructure in Section 7 and a review of commercial experience and technical feasibility in methanol-to-power in Section 8 followed by a summary of key conclusions in Section 9.

3.0 METHANOL MARKET AND APPLICATIONS

Methyl alcohol (CH_3OH) or methanol is the simplest alcohol and is a light, volatile, colorless, and flammable liquid with a distinct odor. In terms of properties, methanol is a biodegradable liquid at room temperature, has nearly half the energy content of diesel, burns with an invisible flame, and is compatible with fuel oil and diesel infrastructure. It is, however, highly toxic and unfit for human consumption. Similar to fuel oil, methanol can be transported and stored in pipelines and tanks made of steel. However, because methanol is an electrically conductive liquid, it is more corrosive than fuel oil at room temperature and therefore small and relatively inexpensive modifications are required to existing fuel oil storage and transportation infrastructure. Exhibit 2 lists key methanol, diesel, and fuel oil properties.

Exhibit 2. A comparison of the physical properties of methanol, diesel, and fuel oil #2.

Fuel	Molecular weight (g/mol)	Density (kg/M³ at 30˚C)	Flash point (°C)	Auto-ignition temperature (°C)	Lower heating value (Btu/gal)
Methanol	32.04	793	12 - 41	470	57,250
Diesel	140.27	820	52	256	128,488
Fuel oil #2	114.23	719	-43	280	116,090

Methanol can be produced from any feedstock that can be converted into synthesis gas (syngas) and it is typically produced from natural gas or coal using a two-step catalytic process. Catalytic reforming is the first step during which natural gas or coal is converted to syngas. In the second step, syngas is converted to methanol. The methanol market is well established with multiple production plants and end uses. Methanol is produced primarily from natural gas in the U.S. and from coal in China. Other prominent methanol producing countries include Canada, Chile, Egypt, New Zealand, and Trinidad and Tobago.

Exhibit 3 shows both global and North American demand and production capacity for methanol. Global methanol production capacity exceeds demand but some of that capacity is old or idled and unlikely to be used. As such, new methanol capacity that is economically viable is being built and U.S. methanol production capacity is anticipated to grow from 5.2 to 15.6 mtpa by 2020.

Exhibit 3. Estimated global and North American demand and capacities show significant growth in global demand and North American capacity through 2020.[1]

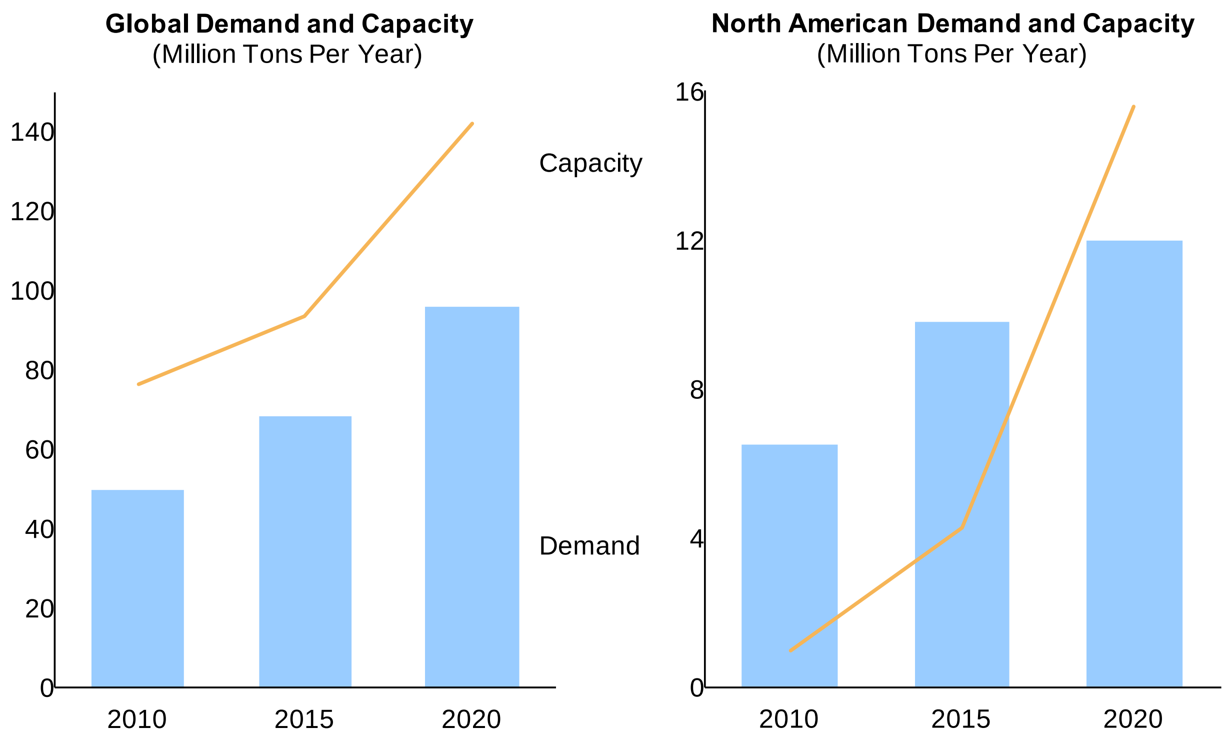


Exhibit 4 shows methanol demand by region. China accounts for a little over 50% of methanol demand followed by other parts of Asia and North America. China is a large and growing consumer of methanol as it uses methanol as a transportation fuel and as a feedstock to produce olefins such as propylene.

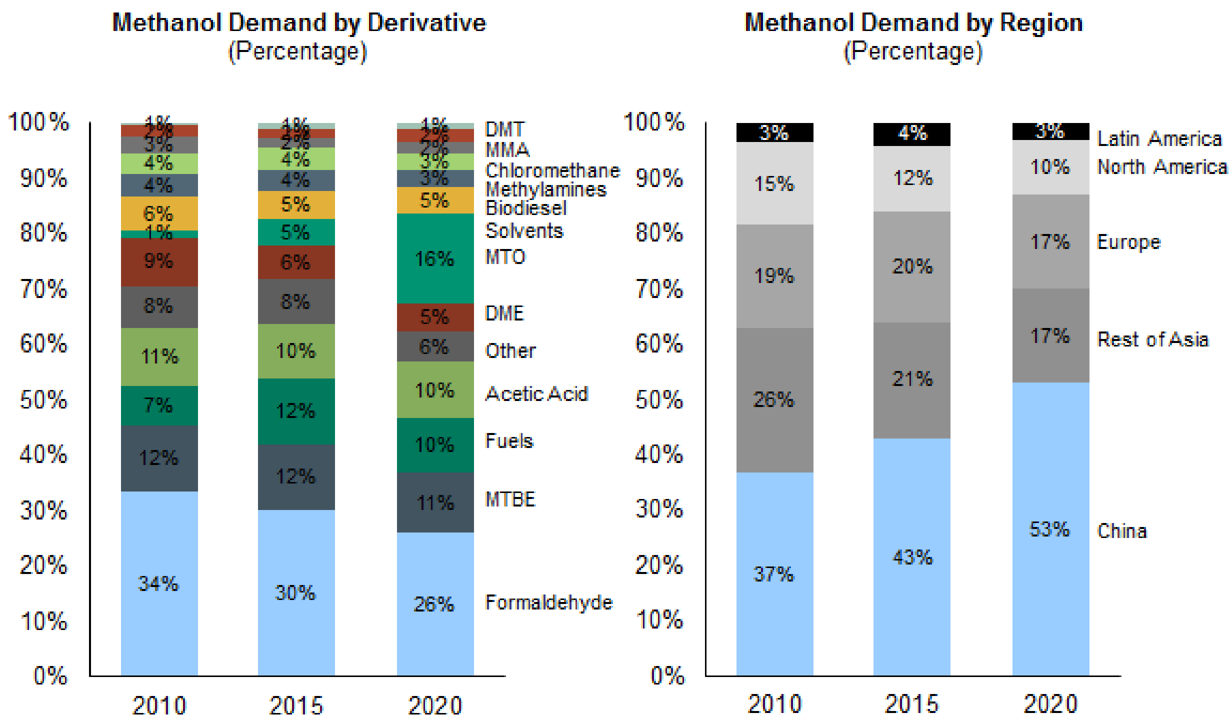
A breakdown of methanol demand by application is also provided in Exhibit 4. Each of these applications can be segmented into three major categories. The first category, which accounts for about 60% of global methanol demand, is the use of methanol as a chemical feedstock to produce derivatives such as formaldehyde and acetic acid as well as olefins that are collectively used to produce numerous products including building materials, foams, resins, plastics, and paints.

The second category accounts for approximately 30% of methanol demand and relates to its use for energy and fuel applications. Such applications including using methanol to produce derivatives such as methyl *tertiary*-butyl ether (MTBE), di-methyl ether (DME), and biodiesel

[1] IHS; Methanex Corporation; MMSA; Jim Jordan & Associates; Reuters; ADI Analytics

that are typically used as fuel blendstocks or additives. For example, MTBE is a proven octane-enhancing gasoline additive whose use in fuels has been banned in the U.S. but allowed in several other countries. Similarly, DME's application as a diesel substitute is being developed and explored in the U.S. and Europe. Finally, methanol is also used to produce biodiesel, which is typically blended with diesel in several regions including U.S. and Europe.

Exhibit 4. Methanol is a key building block for a variety of industrial and commercial products with chemical derivatives and fuel uses in Asia accounting for most of its demand.[2]



An emerging market for methanol demand, growing at a 5.5% rate over the last five years, is its use for fuel applications such as for automobiles, marine vessels, and power generation. Methanol is an attractive alternative fuel because of its cheap production costs, clean fuel benefits, and compatibility with the existing fueling infrastructure. Several countries are using and/or testing methanol as an automotive fuel including China,[3] Israel,[4] Iceland,[5] India,[6] and

[2] Methanex Corporation, 2012 - 2016 Annual Reports, 2016; ADI Analytics

[3] Methanex Corporation, "2015 Responsible Care & Sustainability Report,", 2015

[4] A. Bonshtien, "Fuel Choices Initiative: Israel's Fuel Choices Initiative", 2013

[5] "CRI Unveils Geely M100 Car in Iceland", http://www.methanolfuels.org, Accessed 9 Feb 2017

Australia[7]. China is the biggest user of methanol as a fuel and offers gasoline ranging blended with methanol in volumes ranging from 5% (M5) to 100% (M100) of the fuel. Most of the automobiles using methanol in China are light-duty trucks or public transit vehicles. Finally, methanol has also been used as a fuel for marine vessels and power plants as described later in this white paper.

A final category combines methanol's use in several small and fragmented applications such as solvents, waste water treatment, antifreeze, and ethanol denaturing collectively accounting for about 10% of methanol demand. Methanol's use as a solvent is increasing as it is relatively inexpensive, compliant with regulations, and has an appropriate polarity index that enables dissolution of many compounds. In municipal and private wastewater treatment facilities, methanol facilitates nitrogen removal from effluent streams and denitrification to accelerate the activity of anaerobic bacteria that break down harmful nitrate.

Due to its many end uses and applications, methanol is produced, consumed, traded, and shipped around the world. Methanol can be transported by vessels, inland barges, rail, or tank trucks. Inland barges, railcars, and tank trucks being the most common for domestic transit while marine vessels are used for international transit. Global methanol demand and trade is facilitated by an extensive transportation and shipping infrastructure spanning 2,800 cargo ships, 47,000 barges, and 700,000 rail cars.[8] In addition to this significant existing infrastructure, extensive safety and handling protocols have been developed in collaboration with multiple stakeholders in methanol's well-established and -developed market.

[6] A. Dutta, The Economic Times, May 4, 2017, http://energy.economictimes.indiatimes.com/news/oil-and-gas/we-are-targeting-15-per-cent-methanol-blending-in-the-next-few-years-v-k-saraswat-member-niti-aayog/58517908, Accessed June 4, 2017

[7] Methanex Corporation, "Methanol Fuel Benefits", 2016

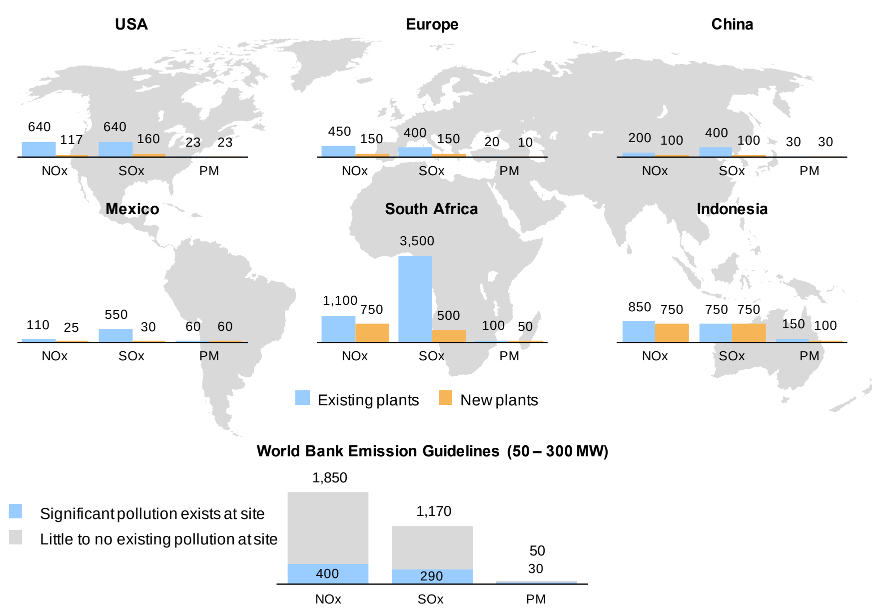
[8] Methanol Institute, http://www.methanol.org/, Accessed June 4, 2017

4.0 ENVIRONMENTAL IMPACT

An important benefit of using methanol as fuel for power generation is that it is clean burning and significantly reduces emissions compared to fuel oil and diesel. There is growing concern for emissions from power plants with new emphasis on lowering NOx, SOx, particulate matter, and CO_2 emissions. Examples include proposed or adopted regulations such as the Mercury and Air Toxics Standards for power plants in the U.S. and the Large Combustion Plant Directive in the European Union. Emission limits vary around the world with a selection presented in Exhibit 5.

Many countries have mandated dramatically lower SOx and NOx emission limits for new power plants in comparison to existing plants. Even emerging economies such as China, Mexico, and Indonesia are regulating power plant emissions. Finally, multilateral agencies such as the International Finance Corporation (IFC), a part of the World Bank Group, have defined environmental, health, and safety guidelines including emission limits for thermal power plants seeking financing.

Exhibit 5. Emission regulations for new and existing power plants are becoming more stringent. [9, 10]



[9] X. Zhang, "Emission Standards and Control of $PM_{2.5}$ from Coal-Fired Plants", IEA Clean Coal Centre, July 2016
[10] IFC, "Environmental, Health, and Safety Guidelines for Thermal Power Plants", 19 December 2008

Power plant operators can comply with these emission regulations by investing capital in emission control technologies such as, among others, ultra-low or low NOx burners, selective catalytic or non-catalytic reduction systems, scrubbers, electrostatic precipitators, fabric filters and baghouses, or carbon capture and storage as shown in Exhibit 6. However, many of these technologies are expensive leading power plant operators to consider cleaner fuels to replace diesel and fuel oil.

Exhibit 6. Emission control technologies exist but are expensive.[11, 12, 13, 14, 15]

	Control technology	Capital cost ($ / kW)
NOx	Selective catalytic reduction system	147 – 221
	Selective non-catalytic reduction system	9 – 35
	Combustion controls	9 – 36
SOx	Limestone forced oxidation scrubber	388 – 747
	Lime spray dryer scrubber	407 – 783
	Dry sorbent injection	5 – 10
PM	Electrostatic precipitators	5 – 27
	Fabric filter/ baghouse	2 – 5
CO2	Carbon capture and storage	594 – 665
	Oxy combustion	1,100 – 1,400

Diesel and fuel oil use in power plants leads to high levels of NOx, SOx, CO_2, and particulate matter emissions during combustion. Each of these emissions stem from different factors. For

[11] EPA, "Emission Control Technologies", 2012
[12] L. Tran, H. Frey, "Methods for Evaluating the Costs of Utility NOx Control Technologies", NCSU Department of Engineering, 960RP139.06, June 1996
[13] C. Weilert, "Wet ESP vs. Sorbent Injection for SO_3 Control", Paper #107
[14] L. Carter, "Retrofitting Carbon Capture Systems on Existing Coal Fired Power Plants", APPA, November 2007
[15] R. Varagoni, F. Chatel-Pelage, P. Pranda, M. Rostam-Abadi, Y. Lu, A. Bose, "Performance Simulation and Cost Assessment of Oxy Combustion Process for CO2 Capture from Coal-fired Plants", May 2005

example, the temperature during combustion of diesel and fuel oil is so high that it produces NOx from both nitrogen in the air that is fed with the fuel as well as fuel-bound nitrogen. In contrast, methanol burns at a lower temperature producing fewer NOx emissions.[16]

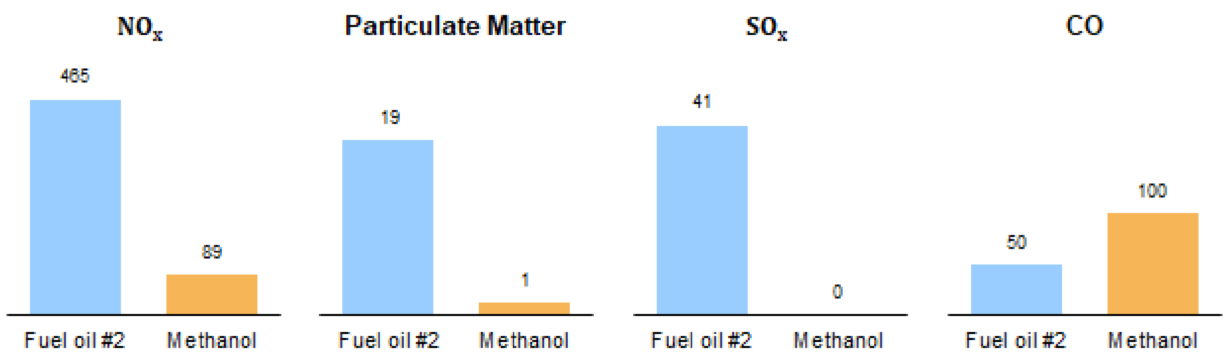
Similarly, sulfur compounds and heavy hydrocarbons in diesel and fuel oil are converted to SOx and particulate matter, respectively, during combustion. In contrast, methanol does not contain sulfur or heavy hydrocarbons thereby precluding the production of SOx and particulate matter emissions. Further, methanol also burns in a visually clearer manner, which is another incentive for islands and regions where tourism is important to their economies.

Exhibit 7 compares emissions from fuel oil #2 and methanol at the Eilat power plant in Israel, the largest power plant in the world currently operating on dual-fuel methanol. Significant reductions in NOx, SOx, and particulate matter emissions were observed when methanol was used as a fuel relative to power generation using fuel oil #2. Emissions of the oxides of sulfur were completely eliminated when methanol was used as a fuel, while particulate matter emissions fell by about 95% and NOx emissions by 80%.

Even so, carbon monoxide emissions were much higher when the gas turbine was operating at low loads during which the combustion temperature is low and methanol is being fired with excess air. However, there are studies indicating that CO emissions are lower when plants run on fuel oil #2 but running plants on methanol becomes more competitive when operating at full loads or loads exceeding at least 80%.[17] Finally, operating methanol-fired power plants at full load also eliminates the formaldehyde emissions typically observed during turbine start-up and partial loads.[18]

[16] Y. Hain, B. Chudnovsky, A. Talanker, A. Kunin, N. Rappoport, M. Rreshef, M. Shternshus, S. Baitel, "Methanol Fuel as Low Cost Alternative For Emission Reduction in Gas Turbines and Utility Boilers", 2012
[17] IEC, Dor Chemicals, "Preliminary Report GT Performance with Methanol Firing After Retrofit", Unit No. 3, 2014
[18] MHPS, "Discussion Material for Methanol-to-Power", November 2016

Exhibit 7. The Eilat power plant in Israel has reported lower SO_x, NO_x, and particulate matter emissions and higher CO emissions when operating with methanol at 60% GT load.[19]

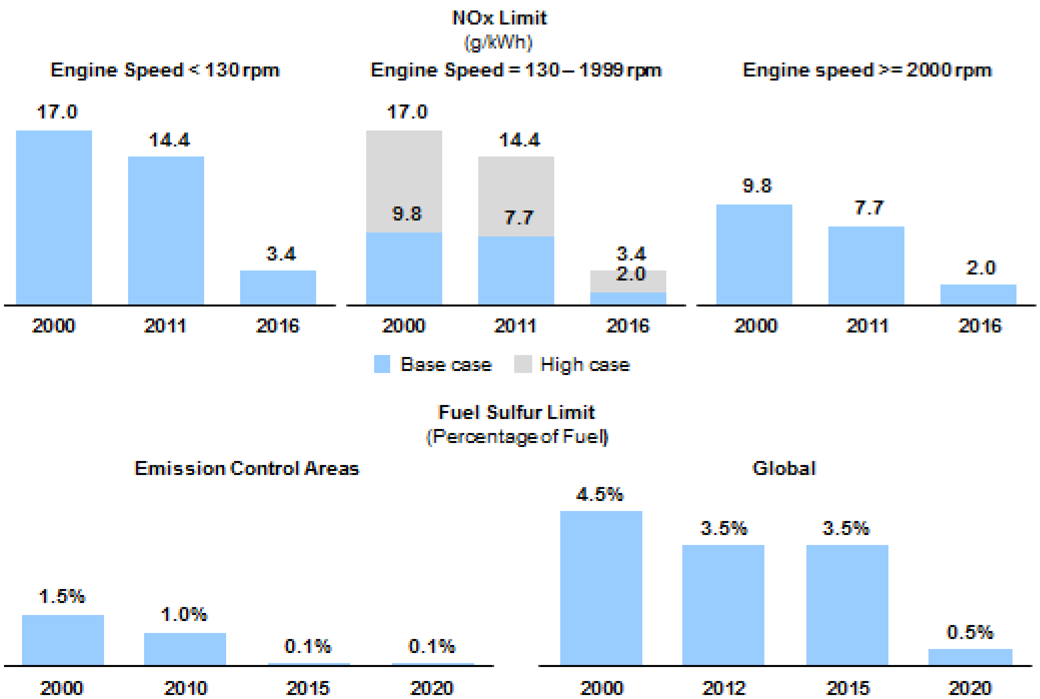


Lower emissions associated with methanol burning are also incentivizing marine applications where regulations are becoming more stringent. The International Maritime Organization (IMO) has been regulating the sulfur content of marine fuels and emissions from engines in marine vessels. A selection of IMO regulations is provided in Exhibit 8. Starting in 2020, the global limit on sulfur in marine fuels will be reduced to 0.5% from 3.5% currently and lower NOx limits based on engine speed and year of construction. In comparison, the sulfur limit for marine fuels used in Emission Control Areas (ECAs) was reduced to 0.1% starting 2015.

Methanol can enable ships to meet these requirements with minor engine modifications. In March 2015, Stena Line, one of the largest ferry operators in northern Europe, retrofitted the *Stena Germanica*, which previously operated on heavy fuel oil, with a dual-fuel Wärtsilä engine capable of operating on methanol with marine gas oil (MGO) as a back-up fuel. The new conversion project enabled the ferry to reduce SOx emissions by 99%, NOx by 60%, CO2 by 25% and particulate matter by 95%.[20] The *Stena Germanica* ferry is now operating in emission control areas subject to the new IMO regulations suggesting methanol-fired marine vessels' ability to comply with the stricter emission regulations.

[19] IEC, Dor Chemicals, "Preliminary Report GT Performance with Methanol Firing After Retrofit", Unit No. 3, 2014
[20] Ship Technology, "*Stena Germanica* RoPax Ferry, Sweden", 2015 Web. Accessed 9 February 2017

Exhibit 8. IMO has placed limits on sulfur in marine fuels and NOx emissions from marine engines in emission control areas.[21]



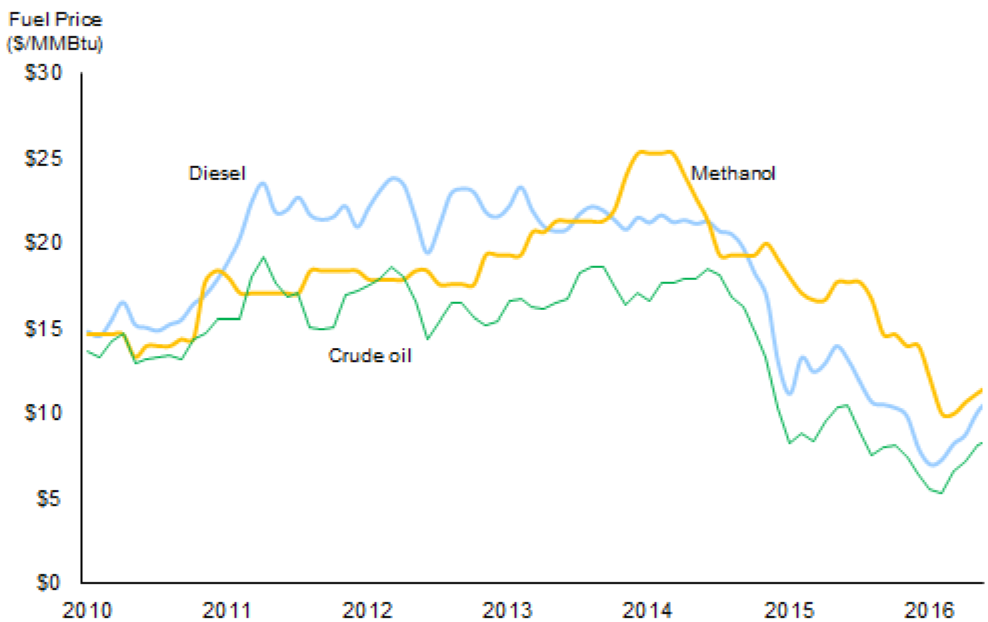
[21] "Prevention of Air Pollution from Ships", http://www.IMO.org, Accessed 9 February 2017

5.0 COST AND PRICING COMPETITIVENESS

Methanol and diesel prices have historically been correlated to that of crude oil as shown in Exhibit 9. However, North American methanol pricing has the potential to be more competitive than other fuels especially if methanol producers start contracting it at prices indexed to the Henry Hub natural gas spot price.

Such a pricing mechanism could offer lower volatility and stable prices for methanol because natural gas accounts for more than 80% of the variable cost of methanol production on the U.S. Gulf Coast. Further, natural gas prices in the U.S. are expected to stay low due to the surplus from the North American shale plays. This is particularly likely with methanol players that are integrated across the value chain, i.e. own natural gas reserves, methanol production plants, and distribution and marketing infrastructure. In addition, long-term structured methanol supply contracts may offer prices below spot/short-term contract methanol prices. Finally, methanol supply contracts can include flexible pricing mechanisms (e.g., indexed to oil or potentially natural gas), price caps and / or floors, and variable volumes and tenors.

Exhibit 9. Historical U.S. Gulf Coast spot prices for diesel, crude oil, and methanol.[22]



[22] EIA, Methanex Corporation

6.0 COST AND ECONOMIC ANALYSIS

Small to medium-sized power plants isolated from cheap diesel and natural gas supply are the likely target market for methanol as a fuel for power generation. Diesel end-users often pay a premium to secure small volumes of diesel supply in addition to transportation and storage costs. Further, given the widespread end-uses of diesel and fuel oil, small power plants often must compete with a number of other customers during supply disruptions caused by weather or refinery turnarounds.

LNG sourcing can be difficult for small or remote power plants as liquefaction plants prefer larger consumers (e.g., utilities in Asia) who are willing to sign long-term offtake contracts that are necessary to finance capital-intensive liquefaction plants. Further, small or remote power plants often need to invest in or have access to regasification plants, which also require capital investment and are often financed by a large base of customers in the importing region. Additionally, methanol can be procured from a wider range of plants in comparison to LNG whose supply contracts are often linked to a specific plant although the share of the spot trade market is growing.

Levelized cost of power generation using methanol was estimated and compared to using LNG and diesel as fuel sources. Economics were estimated for a hypothetical 50 MW power plant assumed to be operating at the same capacity factor across all fuels and having the same base capital cost with adjustments (labeled as "incremental capex" in Exhibit 10) for additional equipment (e.g., storage tanks, safety tools, etc.) necessary to retrofit the plant so it is ready to use methanol or LNG. It should be noted that the incremental capex does not include the cost of a regasification terminal for LNG supply. LNG fuel cost includes capital recovery charges for a regasification terminal that will support a number of other facilities in addition to the 50 MW power plant hypothesized in this case. A common set of other financial and operational assumptions, e.g., interest rate, turbine heat rate, fuel heating values, operating costs, and plant life, were assumed based on estimates provided in literature[23] and summarized in Exhibit 10.

Based on these assumptions, Exhibit 10 shows that levelized costs of power produced using methanol were lower in comparison to that from LNG or diesel. Although methanol is promising as a fuel for power generation, commodity prices are volatile and pose risks to the competitiveness of methanol in comparison to other fuels. However, this risk can be reduced if a producer is willing to sell methanol through a long-term contract linked to the price of natural gas, which can be hedged, has high trading liquidity, and may be less volatile in oversupplied North America. Therefore, operators considering switching to methanol as a fuel for power

[23] R. Murray, H. Furlonge, "Market and Economic Assessment of Using Methanol for Power Generation", The Journal of the Association of Professional Engineers of Trinidad and Tobago, Vol. 38, No. 1, October 2009

generation should carefully develop methanol sourcing strategies to ensure competitive power generation rates across multiple commodity price cycles.

Exhibit 10. Levelized cost analysis of methanol, LNG, and diesel for power generation.[24]

	Methanol	LNG	Diesel
Incremental capex, $ Million	$4	$17	
Heating value MJ / kg	22.7	0.082	42.3
Annual fuel need Million tons	0.22	61.6	0.12
Fuel cost Per ton	$283	$1.08	$734
Annual fuel cost, $ Million	$62.8	$66.8	$87.3
Fuel cost, Cents / kWh	15.92	16.94	22.16
Operating cost, Cents / kWh	2.50	2.50	2.50
Capital cost recovery, Cents / kWh	0.42	0.80	0.30
Levelized cost, Cents / kWh	**18.84**	**20.25**	**24.95**

Capacity, MW	50
Availability	90%
Generation, MWh/year	394,200
Base capital cost, $ Million	$10
Heat rate – turbine, MJ / kWh	12.77
Interest rate	10%
Plant life, years	20

7.0 INFRASTRUCTURE COMPATIBILITY

A key advantage for methanol as a fuel for power generation is that it is a liquid at room temperature and is therefore compatible with existing diesel and fuel oil infrastructure with few inexpensive modifications. Exhibit 11 compares the different transportation, harbor, and storage systems needed for various fuels. These infrastructure compatibility advantages allow operators to retrofit power plants for methanol use cost effectively and quickly – within one to two years – while natural gas and LNG infrastructure can take up to twice as long.

Exhibit 11. Fuel compatibility with existing power plant infrastructure.[24]

	Diesel / Fuel oil	LNG	Methanol
Transportation	▪ Trucks ▪ Marine vessels	▪ Depending on inventory it may require multiple vessels, and partial loading and offloading ▪ Cryogenic materials needed	▪ Multiple vessels ▪ Partial loading and offloading is dependent upon inventory
Harbor	Uses existing harbor	▪ Deep-water harbor and compressors ▪ LNG offloading facilities must be developed	Uses existing harbor
Storage and other infrastructure	▪ Uses existing fuel import facilities ▪ Does not require modifications	▪ New storage infrastructure ▪ Regasification plants	▪ Uses existing fuel import facilities ▪ Requires minor modification
Implementation time (years)	Already available	> 3	1 – 2
Supply flexibility	High	Medium	High

Distribution, handling, storage, and bunkering systems for methanol are similar to those already used today for diesel and fuel oil. Minor modifications that are typically required to use methanol as a fuel for power generation include adapting the fuel supply and injection systems to allow for higher fuel flow rates, installing an internal floating roof on storage tanks to reduce

[24] Y. Hain, B. Chudnovsky, A. Talanker, A. Kunin, N. Rappoport, M. Reshef, M. Shternshus, and S. Baitel, "Methanol Fuel as Low Cost Alternative For Emission Reduction in Gas Turbines and Utility Boilers", 2012

methanol evaporation, upgrading storage and infrastructure material to minimize corrosion, and modifying existing safety systems to assist with methanol flame prevention and detection.

Unlike LNG, methanol does not require large capital investments for ships and storage tanks with cryogenic materials and regasification and import terminals. As such, methanol is particularly attractive to small markets such as islands and remote regions as it can be shipped cost-effectively in small volumes.

8.0 COMMERCIAL EXPERIENCE AND TECHNICAL FEASIBILITY

Commercial experience with the use of methanol for power generation is limited but promising. Exhibit 12 profiles two companies that have explored methanol use for power generation using gas turbines that have ranged from 9.7 to 50.0 MW.

In 2014, Israel Electric Company and DOR Chemicals retrofitted a 50 MW gas turbine power plant enabling it to switch from fuel oil #2 to methanol. Since switching from fuel oil to methanol, the plant has operated comparably to when using fuel oil and reported successful emission reductions. It is currently the only operating methanol-fueled power plant. Similar benefits were seen when Methanol Holdings Trinidad Limited (MHTL) and Proman Group partnered to develop a 9.7 MW commercial-scale methanol-to-power project in Trinidad and Tobago based on a MAN Diesel & Turbo turbine.

Exhibit 12. Profiles of select methanol-to-power projects around the world.

Project	Companies	Location	Description
Trinidad and Tobago	MHTL and Proman Group	Trinidad and Tobago	▪ Retrofitted a 9.7 MW Gas turbine from diesel to methanol in 2007
Eliat power plant	DOR Chemicals and Israel Electric Company	Eliat, Israel	▪ Retrofitted a 50 MW Gas turbine power plant from fuel oil #2 to methanol in 2014 ▪ Results yielded significant decreases in NOx and SOx emissions … ▪ … while CO emissions from methanol neared that of fuel oil #2 as gas turbine load increased

In studies conducted by GE, Wartsila, and Mitsubishi Hitachi Power Systems (MHPS), original equipment manufacturers (OEMs) have indicated that it is feasible to retrofit or produce new engines or turbines to produce power from methanol. Exhibit 13 summarizes OEM initiatives and feedback from interviews ADI conducted with OEMs for this white paper. Overall, OEMs who have conducted feasibility studies or have active projects acknowledge the benefits of methanol-to-power. GE, MAN Diesel & Turbo, MHPS, Siemens, and Wärtsilä all view methanol as either a superior or promising fuel as it can help meet increasingly stringent emission regulations while having an excellent heat rate and high power output.

Exhibit 13. Several OEMs have expressed interest in methanol-to-power and have conducted technical and economic feasibility studies.[25, 26, 27, 28, 29]

GE	▪ Conducted test with modified gas turbines utilizing methanol in 1974 at the Bayboro Station of Florida Power Corporation and in 1978 and 1979 at SCE's Ellwood Energy Support Facility ▪ Published a whitepaper assessing the technical feasibility of utilizing methanol in gas turbines in 2001
MHI	▪ Assessed the technical feasibility of methanol to power throughout the 1990's ▪ Believes it is possible to complete retrofitting work during the overhaul maintenance period (~30 days) if the methanol supply system is arranged as a mechanical skid in advance
WÄRTSILÄ	▪ Conducted the world's first diesel to methanol ferry retrofit on the Stena Germanica ▪ Retrofitted four engines for the Stena Germanica between 2015 and 2016 and believes conversion cost of future retrofits will drop drastically as experience mounts
MAN	▪ Partnered with Proman Group in 2007 to develop a 9.7 MW methanol-to-power project ▪ Built seven new-build methanol dual-fuel engines for Methanex's Waterfront Shipping after concluding the ability to run an engine on sulfur-free fuels offers great potential
SIEMENS	▪ Assessed and tested the technical feasibility of retrofitting a Siemens gas turbine for alternative fuels ▪ Determined methanol is an excellent fuel and methanol-based power generation is almost economically competitive with natural gas and fuel oil

With regard to methanol as a marine fuel, the *Stena Germanica* was retrofitted in March 2015 with a dual-fuel Wärtsilä engine capable of operating on methanol. A year later, in April 2016, Waterfront Shipping chartered seven methanol ocean tankers equipped with engines from MAN Diesel & Turbo that can run on various fuels including methanol. Although the *Stena Germanica* retrofit cost was approximately $600 per kW of power output, future conversions are expected to be cheaper (around $400 per kW) with experience.[30] These marine retrofits further demonstrate the technical feasibility of using methanol as a fuel for power generation because ships use engines similar to those used in power plants manufactured by the same OEMs that require similar changes.

[25] GE, "Feasibility of Methanol as a Gas Turbine Fuel", GE Position Paper, 13 February 2001
[26] MHPS, "Discussion Material for Methanol-to-Power", November 2016
[27] A. Borgmastars, "Fuel Flexible Power Plants from Wartsila", Wartsila Technical Journal, 13 October 2016
[28] MAN Diesel & Turbo, "Using Methanol Fuel in the MAN B&W ME-LGI Series", August 2014
[29] H. Kliemke, T. Johnke, "Gas Turbine Modernization – Fuel Conversion and Special Fuel Applications for the Asian Market, October 201
[30] K. Andersson, C. Salazar, "Methanol as a Marine Fuel", FCBI, 2015

In general, feasibility studies and operational experiences suggest that methanol's use for power generation is feasible, economical, easy to implement, and cuts emissions. Specifically, when methanol is used as a fuel for power generation, NOx and SOx emissions were reduced significantly and CO emission reductions varied based on operating loads. Gas turbine, boiler, and reciprocating engine performances either improved or remained unchanged.

Although minor, OEMs have pointed out a few technical and operational considerations for operators interested in retrofitting power plants. Key issues include finding appropriate equipment, adapting fuel supply system, optimizing fuel unloading and storage, updating safety equipment and process. Each of these are detailed below.

1. **Finding appropriate equipment:** Based on conversations with Israel Electric Company, each power generation unit is designed and optimized for traditional fuels such as natural gas, diesel, or fuel oil. Switching such systems to non-traditional fuels such as methanol requires minor equipment modifications. Gas turbines and reciprocating engines are available but OEMs would need lead time to retrofit them for methanol.

2. **Adapting fuel supply system:** In comparison to diesel, methanol has half the heating value and, therefore, a larger volume of methanol is needed to ensure the same level of power generation. Fuel nozzles in plants designed for oil-based fuels are too small for higher methanol flows and would have to be replaced by high-flow fuel nozzles. Existing shaft-driven fuel supply pumps are replaced with external electric high-pressure pumps which are designed to have two branches, one for diesel light fuel and another for methanol with associated gate valves. Modulating valves need to be replaced with either higher-capacity valves or by a variable speed drive, which controls the fuel flow remotely from a control room. Pressure and dump valves along with their associated pipes also require replacing with pipes with larger diameters to allow for higher fuel flow. [31]

   Methanol also has a higher vapor pressure than diesel. In order to prevent combustion instability by vapor lock, another fuel should be used (such as diesel) for ignition, start-up and lower loads. A dual-fuel plant will require a changeover system to switch between fuels. This is needed to minimize the risk of corrosion in equipment that was not originally designed to run on methanol as methanol can be corrosive at ambient temperatures.

3. **Upgrading storage and unloading systems:** Methanol has a lower boiling point relative to diesel, evaporates easily, and is very combustible. Existing diesel storage and unloading systems can be modified to handle methanol, or new systems can be added for dual-fuel capability for unloading systems.

[31] B. Chudnovsky, M. Keren, M. Reshef, S. Baitel, "Successfully Implementation of Methanol Firing At 50 MW Gas Turbine For Long Term Operation", ASME Power & Energy 2015 Power & Energy, July 2015

Also, an internal floating roof would have to be installed inside the storage tank to reduce methanol evaporation. Internal floating roof storage tanks also minimize vapor space within a tank and reduce the amount of air available to mix with methanol vapor.[32] Inert gas blanketing or padding would also have to be considered to add an additional level of protection against ignition within the tank. Some systems may also use dry nitrogen for blanketing as it preserves methanol purity.

Fuel unloading and piping systems may also need to be upgraded. Upgraded unloading piping systems should have two forwarding pumps to bring methanol to the injection skid. In some cases, vapor recovery units may need to be implemented. A larger storage tank would also be required as twice as much methanol is needed to produce the same amount of power as diesel.

4. **Modifying safety systems:** Methanol's low flame temperature and invisible flame may require special flame detection equipment. Infrared video cameras have been used in some instances to assist with methanol flame detection. The firefighting system may also have to be modified to use alcohol-resistant foams such as film-forming fluoroprotein foam that can activate in the presence of methanol. Vapor detectors may also have to be considered as large quantities of vapor can cause ignition and possible flashback. Additional protective gear for personnel handling methanol will likely also be required. [33]

5. **Other:** Methanol is more corrosive and toxic than other fuels and operators should evaluate their plants to ensure their equipment is compatible and tolerant of methanol. Seals, O-rings, and other handling equipment should be replaced with methanol-compatible equipment. Using a fuel changeover system to start and stop with diesel or similar fuels will minimize the risk of corrosion in equipment that was not originally designed to run on methanol.

[32] B. Chudnovsky, M. Keren, M. Reshef, S. Baitel, "Successfully Implementation of Methanol Firing At 50 MW Gas Turbine For Long Term Operation", ASME Power & Energy 2015 Power & Energy, July 2015

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9.0 CONCLUSIONS

- Interest in methanol as a fuel for power generation is growing for multiple reasons. First, it is cleaner-burning than diesel or fuel oil and can help power plants meet increasingly stringent emission regulations. In comparison to diesel, burning methanol for power generation can reduce NO_x emissions by 80% or more. Also, methanol does not contain sulfur or heavy hydrocarbons thereby precluding SO_x and particulate matter emissions. Finally, complete combustion of methanol creates fewer CO_2 emissions in comparison to diesel.

- Second, abundant, cheap supply of natural gas from shale plays in North America has led to several announcements of new methanol plants potentially shifting the U.S. from a methanol importer to an exporter. Further, it may be possible in the future to negotiate long-term supply contracts for methanol at attractive prices linked to U.S. natural gas prices.

- Third, power plants located in remote locations are interested in methanol-to-power due to constraints with natural gas sourcing and infrastructure. Finally, power plants can be retrofitted to use methanol as a fuel more quickly and easily in comparison to LNG and other alternative clean fuels.

- Methanol is compatible with existing diesel and fuel oil infrastructure. Relative to LNG and LPG and the infrastructure needed to transport such fuels, retrofitting an engine for methanol has lower capital cost and minimal infrastructure requirements.

- Based on various operational and financial assumptions for a power plant, levelized costs of power produced using methanol are lower in comparison to that from LNG or diesel. However, operators should carefully develop methanol sourcing strategies to produce power at competitive costs across multiple commodity cycles.

- Two power plants in Israel and Trinidad and Tobago have successfully used methanol for power generation using gas turbines ranging from approximately 10 to 50 MW in capacity. Operators considering retrofitting their power plants to enable the use of methanol as a fuel should carefully develop plans to address key technical and operational issues including specifying and procuring retrofit equipment, negotiating methanol supply contracts, optimizing fuel unloading and storage systems, and updating safety processes.

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