the Energy to Lead

REPORT

GTI PROJECT NUMBER 20847

Expert Analysis of the Concept of Synthetic and/or Bio-LPG

Report Issued
February 19, 2010

Prepared For
Mr. Gregory Kerr
Director, Research and Development
Propane Education and Research Council
1140 Connecticut Ave NW, Suite 1075
Washington, District of Columbia 20036
(202) 452-8975 Ext: 2021
Gregory.kerr@propanecouncil.org

GTI Technical Contact
Dr. Arun Basu
Institute Engineer
847-768-0509
Arun.basu@gastechnology.org

Gas Technology Institute
1700 S. Mount Prospect Road
Des Plaines, Illinois 60018
www.gastechnology.org

I. Legal Notice

This information was prepared by Gas Technology Institute ("GTI") for Propane Education and Research Council.

Neither GTI, the members of GTI, the Sponsor(s), nor any person acting on behalf of any of them:

a. Makes any warranty or representation, express or implied with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately-owned rights. Conclusions and analysis of information gathered or generated for this report represent GTI's opinion based and with respect to which competent specialists may differ.

b. Assumes any liability with respect to the use of, or for any and all damages resulting from the use of, any information, apparatus, method, or process disclosed in this report; any other use of, or reliance on, this report by any third party is at the third party's sole risk.

II. Table of Contents

III. List of Figures and Tables

Page

1 Executive Summary

1.1 Purpose and Background

In the current U.S. energy environment, there is significant emphasis on energy independence and concerns for climate change due to the use of fossil fuels including conventional LPG. The sustainable production of renewable and synthetic fuels (with CO_2 recovery plus sequestration) is also receiving significant attention from private industries and government agencies. The total annual bio-energy potential in the U.S. is estimated to be about 350 million tons to about one billion tons (Figure 1 Estimates on Bioenergy Potential in the U.S.; DOE/EIA/USDA); this includes agricultural and forest residues, energy crops and urban wood waste. As an example, at a total availability of 500 million tons and 100% utilization, about 2.0 million barrels/day (MMBPD) of bio-crude could be produced. This could be accomplished by using integrated biomass gasification for the production of synthesis gas, primarily a mixture of hydrogen and carbon monoxide, followed by synthesis gas conversion. Of this total bio-crude, about 1,500-6,000 million gallons/year could potentially be bio-propane. As a perspective, during 2008, the total transportation fuel consumption in the U.S. was about 13 MMBPD, while odorized propane consumption was about 10,000 million gallons/year.

An important factor that may possibly influence future propane markets in the U.S. is the ongoing debate over reconciling climate change, energy efficiency and concern for the environment. An example is the recent EPA proposal in revising the National Renewable Fuel Standard program (known as the RFS program; Appendix B: Table B-1),[1] under the Energy Independence & Security Act of 2007. Under this proposal, the total annual renewable fuel (currently, mostly, ethanol and biodiesel) that (i) should meet specific Greenhouse Gas (GHG) reduction targets (Table B-2), and (ii) must be used in transportation fuel each year would increase from the current 9 billion gallons (Bgal) level in 2009 to about 36 Bgal level (~2.4 MMBPD) by 2022. Another state-level GHG regulation, the Global Warming Solutions Act, AB32, has been enacted in California; which requires monitoring/reporting of GHG emissions and bringing the state's emissions into compliance with the Kyoto Protocol guidelines.[2] In this context, the Propane Education and Research Council (PERC) is interested in developing key R&D and business strategies for the commercial production of bio-propane (e.g., propane derived from biomass feed stocks) and synthetic propane (e.g., propane derived from non-petroleum fossil fuels : natural gas, coal or petroleum coke) based on technical and economic analyses of various promising technologies.

PERC is also interested in evaluating the potential of bio/synthetic DME (Dimethyl Ether; currently used commercially as a high-grade aerosol propellant), as a LPG supplement. Stored and transported like propane, DME is currently attracting worldwide attention as a supplement or alternative for LPG as well as for diesel and LNG applications. The World LP Gas Association (WLPGA) has observed that (i) DME and LPG can often be used, as mixtures or separately, as "substitutes", and (ii) the LP gas industry is ready to welcome the use of DME.[3] Multiple studies, including those by E. I. du Pont de Nemours and Company, have shown that DME is benign, has low toxicity and is non-carcinogenic.[4]

1.2 Current Worldwide LPG and DME Production Volumes

The 2009 total global LPG production was about 245 million metric tons (MMT), and that for DME was about 9 MMT, including new coal-to-DME plant capacity built exclusively in China over the last 5-7 years.[3,5,6] Several private companies are currently evaluating the commercial potential of DME for various markets. As an example, a recent announcement from South Korea's KOGAS indicates that it has signed an agreement with the Saudi Arabian government to build a natural gas-based, 900 tons/day DME plant in Saudi Arabia. Initially, KOGAS will test market demands for specific LPG/DME blendED fuels in Korea.[7] According to the WLPGA, the total global production of LPG and DME by the year 2020 would reach about 340 MMT and 70 MMT respectively.[3,5] Thus, depending on future international prices for petroleum crude, the development of other advanced bio-fuels (e.g., algae-based fuels), and GHG related regulations, commercial production of large quantities of bio/synthetic DME could significantly depress the future demand and price for propane.

1.3 Technologies and Concepts for the Production of Synthetic or Bio-Propane/DME

Currently, there are no commercially proven technologies where the production of synthetic or bio-propane is the predominant product of the process.

1.3.1 Near-term Technologies for Synthetic Propane

- The ExxonMobil MTG (Methanol-to-Gasoline)[8] technology is a key commercially proven technology to produce LPG as a byproduct of gasoline production. The process uses synthesis gas produced from natural gas (NG), coal or petroleum coke; JAMG Inc. of Shanxi, China, started up a 2,500 bbl/day, coal-based MTG plant in 2009.[8] Haldor Topsoe (HTAS) is also developing a competing process (the TIGAS - Topsoe Integrated Gasoline Synthesis - process, demonstrated at a scale of 5 bbl/day) to utilize NG, coal or biomass for the production of gasoline with LPG as a byproduct.[9]

1.3.2 Near-term technologies for Fischer-Tropsch Products

- For Fischer-Tropsch (FT) technologies, which primarily produce diesel from synthesis gas, LPG is also a byproduct, but in much smaller quantities relative to the MTG or TIGAS processes.

1.3.3 Near-term Technologies for Synthetic DME

- Several companies (e.g., Toyo Engineering, HTAS, Lurgi) have developed DME synthesis technologies where DME is the primary product to utilize coal or natural gas. Toyo has already built four coal-based commercial DME plants in China.[10] As DME is an intermediate product in the MTG and TIGAS technologies, these processes can also be modified, if justified based on market demands, to produce DME as a major product.

  It seems that for applications involving biomass gasification, these technologies for the coproduction of gasoline/LPG and for the production of DME would quite likely be commercialized within the next five to seven years; however, specific firms may have proprietary biomass gasification technologies that may shorten this commercialization time frame. For oxygen-blown biomass gasification technologies, in general, a few of the key process steps (e.g., Tar Reforming, synthesis gas clean-up) are still at pilot-plant or demonstration stages. As an example, the Gas Technology Institute (GTI; located in Des Plaines, Illinois) is currently demonstrating the Andritz/Carbona-biomass gasification process at a scale of 20 tons/day of wood. DOE and the U.S. Department of Agriculture (USDA) announced on December 4, 2009 an award to HTAS to demonstrate the Carbona biomass gasification technology integrated with their TIGAS process for a wood-to-gasoline integrated biorefinery projects at GTI.[11] As DME is an intermediate product in this process, this HTAS /DOE program could in effect demonstrate a wood-to-DME process.
  - Preliminary estimates indicate that bio-gasoline production from a MTG type process without any CCS (Carbon Capture & Sequestration) step would reduce total lifecycle GHG emissions by about 75-90% relative to petroleum gasoline.[12] With CCS, significant quantities of coal (and natural gas, NG) can be co-gasified (for NG, a separate steam/oxygen reforming unit would be used) with biomass, and still achieve negative carbon footprints (Figure 4).[8]
  - DME can also be made from synthesis gas derived from oxygen/enriched-air/steam-based gasification of black liquor from paper/pulp mills (e.g., a 5 tons/day Bio-DME demonstration

currently being carried out by a team led by Chemrec AB, Volvo and HTAS).[13] The Chinese Academy of Sciences is also operating a pilot plant to produce ~ 3 tons/day DME from biomass.[14]

1.3.4 Other potential Concepts/Technologies Requiring Significant Additional R&D and Demonstration

Specific novel concepts, for the production of bio/synthetic LPG and DME, mostly demonstrated at the bench-level scale of research, are discussed in Appendix A. As might be expected, these will require significant R&D investment before they could be considered as candidates for commercialization. As mentioned in our Recommendations, PERC may possibly monitor and focus their efforts in further evaluation of seven of these novel concepts:

1.3.4.1 For LPG Synthesis (Four Key Technologies)

1. The BioForming process, currently being developed by Virent Energy Systems Inc. (VES)[15] for the production of gasoline and diesel from biomass; the process was initially developed to primarily produce bio-propane.[16] This could be an important technology to produce bio-propane, as VES has been able to form a joint venture with Shell Oil to further develop this process.
2. The Japan Gas Synthesis Co. Ltd. (JGS) process, proven at bench-scale level, [17] for the direct synthesis of LPG (with very high selectivity) from synthesis gas produced from natural gas, coal and biomass.
3. The University of Kitakyushu process for the conversion of DME to LPG using hydrogen.[18] This provides a pathway for LPG production if low-cost DME is available in specific locations, and the demand for LPG is relatively high. This concept, if commercialized, would avoid a key problem for large-scale utilization of DME which, typically, cannot be used in existing LPG infrastructures (e.g., pipelines) with relatively high DME/LPG ratios primarily due to material compatibility issues related to seals, gaskets etc. For plants where DME would be produced from biomass (or coal/NG), a part of the required H_2 for conversion of DME to LPG would be derived from the gasification (or NG- reforming) sections. However, for plant designs involving the conversion of DME itself to LPG, the supply of H_2 would be an important logistical and design issue.
4. The GTI IH^2 process in which LPG would be produced as a by-product with gasoline plus diesel.[19]

1.3.4.2 For DME Synthesis (Three Key Technologies)

1. The Isis Innovation process (being developed at the University of Oxford) to convert glycerol (a byproduct from bio-diesel production) plus H_2 to bio-methanol which can be further converted to bio-DME using commercially available dehydration technologies.[20] If the DME product is to be considered 100% bio-DME, the H_2 used in the process should also be made from renewable sources (e.g., via biomass gasification, or from biogas). Another option would be to convert a part of the feed glycerol to H_2 (e.g., either by using conventional steam-reforming process or by using the GTI POGT – Partial Oxidation Gas Turbine - technology).
2. The GTI POGT (Partial Oxidation Gas Turbine) process for (i) the production of DME from biogas or landfill gas, or for (ii) the production of H_2 from biogas or glycerol.
3. The Carbon Recycling International Inc. (an Icelandic/US company) process now being commercialized to produce methanol/DME from H_2 (e.g., via water electrolysis) and CO_2.[21]

A few of the novel concepts discussed in Appendix A (e.g., the process proposed by the Mississippi State University for catalytic cracking of specific fractions of vegetable oils to produce LPG[22], and the Isis

Innovation process) involve the use of corn or soybean type vegetable oils. Due to the ongoing concerns for the potential increase of food prices in converting such oils to bio-fuels, these concepts would mostly be commercially attractive if the production of low-cost algae-based oils or other non-food crop feedstock can be commercialized.

1.4 Scoping Economic Cases Analyzed in this Study

Four Design Cases were developed to estimate scoping economics for the production of bio/synthetic propane or DME by gasifying wood or coal:

(1) Case A was developed to determine scoping economics for the production of bio-DME via oxygen-blown gasification of biomass,
(2) For Case B, Case A was modified to determine scoping economics for the production of bio-propane from biomass (key catalyst systems for this process are currently being developed by Japan Gas Synthesis Ltd.[17]) with suitable changes in (i) capital plus operating costs for the potentially lower operating pressure for the LPG synthesis reactor : 800 psia vs. about 1,265 psia for DME synthesis and (ii) net production of electric power for sale,
(3) Case C was developed based on a recent publication from ExxonMobil[8] on scoping economics for mega-scale plants (requiring ~ $4 billion of CAPEX), including with CCS, for the production of gasoline (plus LPG and electric power) from coal using the MTG technology, and
(4) For Case D, we used literature data from a DOE/NETL publication[23] to determine scoping economics for the co-production of DME plus electric power via coal gasification in a moderately large-scale plant (~ CAPEX: $1.0 billion).

The key results are summarized in Table 1 and Figure 11; key sensitivities for prices of wood and gasoline on the cost of production of propane are shown in Figure 12. The primary economic assumptions are: (1) plant operating factor: 90%, (2) cost of wood: $40/dry metric ton, (3) coal price: $35/metric ton as-received, (4) electricity: $0.08/kwhr, (5) gasoline selling price: $70/bbl, (6) cost of production includes 13% ROI and (7) no credits for GHG reductions and no government subsidies.

Table 1 Key Results for the Four Economic Cases (July 2009 $)

(Assuming no government credits for renewable fuels or for GHG reductions)

Economic Case	**A**	**B**	**C**	**D**
Gasification Feedstock	**Biomass**	**Biomass**	**Coal**	**Coal**
Products	DME	Propane	Gasoline plus Propane	DME
Feed rate of wood or coal, metric tons/day	3,000 (wood)	3,000 (wood)	23,200 (coal)	3,859 (coal)
Equivalent Propane production, million gallons/yr	69.3	69.3	114.6	118.9
Gasoline for sale, million bbl/yr	None	None	14.5	none
Net electric power for sale, MW	26.3	26.3	111.0	172.8
Net Thermal Efficiency, % (LHV)	45.3	46.0	52.9	53.9
Total capital need, $MM	670*	650 *	4,020 (includes CCS)	1,030*
Base Case Cost of Production (COP) of Propane (or DME as propane Equivalent gallon), $/gallon $/MMBtu (LHV)	2.43** 29.8	2.31 28.3	0.85 10.4	1.35 16.5
Indicative Required Equivalent Petroleum Crude Price, $/bbl***; propane price @65% of crude oil price, in $/gal.	150	143	55	87

***** Partial CO$_2$ recovery; however, with no credits taken for any potential sale of CO$_2$ ** COP would be $2.83/gal if cost of dry wood is $70/metric ton. *** Typically, based on recent price trends, wholesale propane prices (without taxes/transportation costs) in the U.S. vary in the range of 50-80% of crude oil prices in $/gal units.[24]

1.5 Potential New Applications for LPG and DME, Especially for Bio-LPG and Bio-DME

It is possible that due to specific energy policy mandates (e.g., the proposed EPA/RFS program on renewable transportation fuels), significant quantities of bio-LPG, and possibly some bio-DME, may be introduced into the U.S. energy markets during the next five to ten years. As an example, under the EPA/RFS program, if 15% of the required 36 Bgal of renewable fuel per year by 2022 is produced from woody biomass by MTG/TIGAS-type processes, the U.S. could produce approximately 300-1,100 million gallons of propane per year (at 5-20% of gasoline volumes; see Table 2). In order to increase demands for LPG, PERC could possibly consider promoting the following new applications (especially for bio-LPG and bio-DME) that need to be supported by suitable experimental as well as economic and marketing studies:

- *Use of LPG (or LPG/DME blends) as a fuel supplement in existing diesel-fueled engines*. DieselGas Technologies Inc. of Australia has claimed that the addition of propane at ~ 35-40% of total volume of fuel feed in stationary diesel engines used for distributed power generation, and at ~ 20-25% in diesel-fueled vehicles is beneficial in (i) increasing net BHP as well as Torque for an existing diesel engine, and (ii) reducing smoke formation and enhancing engine life by reducing engine wear.[25]
- *Use of LPG for distributed power generation using fuel cells* (e.g., for H$_2$ generation from LPG using GTI's POGT concept).
- *DME as a LPG supplement*. DME can possibly be used as a LPG supplement at the 10-30% level[3, 26] in LPG/DME blends for existing domestic cooking and heating applications without any major equipment modifications. During 2008, about 18.5 million metric tons (MM tons) of odorized propane was used in the U.S.[27] In these markets for odorized propane, at 20 wt% blending level, the U.S. can potentially consume about 4.6 million tons of DME per year (requiring ~ 22 commercial

biomass-to-DME plants, each processing about 3,000 tons/day of wood). However, such market acceptance for DME could result in significant reductions for propane/bio-propane prices.

- *Use of LPG/DME blends fuels for fleet vehicles using SI (spark-ignited) engines.* In the U.S., LPG is the leading alternative fuel; it is also the third most common vehicular fuel.[28] However, recent PERC-sponsored studies[27] indicate that the number of registered LPG vehicles in the U.S. have declined primarily because of (i) competition from other alternative fuels (e.g., ethanol and biodiesel) and vehicles (e.g., hybrid electric vehicles), and (ii) new 2000/2004 EPA/CARB emissions regulations. In this context, it may be helpful to further explore the potential of using LPG/DME blends in SI engines. Studies at British Petroleum (owner of a 1997 U.S. Patent, 5,632,786) and other results[3,29] suggest that Propane/DME blend fuels with about 10-25 wt% DME can be used in specific SI engines. Key emission benefits, relative to the sole use of LPG, include reductions in total CO and unburned hydrocarbon emissions.
- *Production of H_2 from DME.* For LPG-fueled CHP applications as well as for hybrid power systems in LPG-powered vehicles, DME can be used to produce H_2 (via reforming with air and/or steam) for fuel cells. DME requires significantly lower temperatures (e.g., 150-250°C vs. greater than 650°C for methane, ethanol and gasoline; key data for DME is shown in Figure B-5)[30] relative to other fuels for reforming to H_2 with air/steam.
- *LPG/DME fuel partnering.* LPG/DME can be fuel partnered with renewable energy (e.g., solar) to use standalone integrated systems; this concept is being promoted by the World LP Gas Association (Figure B-1).[6]
- *Use of LPG/DME blends*. LPG/DME can be blended for use in forklifts. Note that propane is already used commercially in certain types of forklifts (Class 4 & 5).

1.6 Conclusions

Our key conclusions are discussed in the following sections.

1.6.1 Bio/Synthetic LPG

- The total bio-energy resource base in the U.S. is estimated to be about 350-1,000 million tons (dry)/year.[31,32] Assuming a total availability of 500 million metric tons/yr and 100% utilization, the U.S. can produce about 2 million barrels/day (MMBPD) of bio-crude (as gasoline plus LPG) using MTG/TIGAS-type processes. This represents a potential of approximately 1,500-6,000 million gallons of bio-propane per year as a byproduct.
- As indicated in Table 2, implementation of the EPA/RFS type regulations for mandatory usage of specific quantities of renewable fuels as transportation fuels could introduce significant quantities of bio-LPG (and possibly bio-DME) in the U.S. energy markets.
- The ExxonMobil MTG process is the only commercial technology proven to have produced LPG as a significant byproduct (with gasoline as the major product) from either natural gas or coal. FT-diesel type processes produce insignificant quantities of LPG. As shown in the Case C scenario, a mega-scale MTG plant processing about 23,000 tons/day of coal can typically produce about 0.2 -0.3 million metric tons of propane/year as a byproduct. Domestic use would require about 15-18 such mega-scale coal-based MTG plants to produce 20% of the current demand for odorized propane (~19 million tons/year) in the U.S. However, large-scale construction of such plants would require (i) relatively large capital expenditures, and (ii) the availability of well-proven CCS technologies. For specific locations with access to an existing CO_2 pipeline and EOR markets, new CCS technologies may not be required.
- A competing technology to the MTG process is the TIGAS process being developed by HTAS.

- The lifecycle GHG emission reductions for such MTG/TIGAS-type bio-gasoline, without any sequestration of CO_2 emissions from such plants, would be about 75-90% relative to gasoline derived from petroleum. This also indicates the extent of GHG reduction potential for bio-LPG.
- With respect to the utilization of biomass, the MTG/TIGAS technologies could possibly be ready for commercialization in the U.S. within the next three to five years. Specific firms (e.g., Andritz/Carbona in the U.S.[33], or Choren/Shell[34] in Germany) are currently demonstrating oxygen-based biomass gasification processes in large-scale demo plants (20-200 tons/day biomass feed). HTAS has recently been awarded specific contracts, under a 4-year program starting Jan'2010, by the U.S. DOE to demonstrate the TIGAS technology to produce gasoline from wood at GTI's R&D facilities in Des Plaines, Illinois.
- With the use of suitable CCS technologies, significant quantities of NG and coal (typical estimates are shown in Figure 4) can be co-processed with biomass-based MTG/TIGAS technologies to produce synthetic propane (and DME) and such plants can have relatively low negative carbon footprints.[8,12] Nuon Inc. and Shell have successfully tested co-gasification of coal plus biomass (at 30 wt% wood feed) at their 250 MW IGCC plant in Netherlands; a 1,200 MW IGCC plant using coal plus biomass feed is expected to be fully operational by 2011.[35]
- GTI also has initiated an in-house program (along with specific financial assistance from the DOE under the ARR Act) to develop a new technology, called the IH^2 (Integrated Hydro-pyrolysis and Hydro-conversion) process, that would produce LPG as a byproduct from biomass.
- Various novel concepts (discussed in Appendix A), demonstrated at bench-scale levels, for the production of synthetic LPG have been proposed by various R&D groups. Significant R&D expenses would be required to further develop these technologies. Four of these processes (mentioned in the Recommendation Section) merit further evaluations by PERC.
- Specific process and cost data for the bio-propane process proposed by C3 BioEnergy LLC could not be obtained. Apparently, this concept uses supercritical water to convert biomass to propane with high selectivity.
- DieselGas Technologies Inc. of Australia has claimed the development of a suitable technology for using LPG (at about 20-40% level) as a fuel supplement in existing diesel engines. If the key claims of this technology can be confirmed, a new market for LPG (and possibly also for LPG/DME blends) could possibly emerge.
- GTI's POGT technology, demonstrated at ~ 250 kw power generation level using natural gas and air, can be modified to generate H_2 from LPG for CHP and fuel-cell applications.

1.6.2 Bio/Synthetic DME

- Several technologies have been developed to commercialize the production of DME from synthesis gas derived from coal and natural gas. Some have been commercialized; e.g., the Toyo Engineering process. However, for DME production from biomass (including black-liquor from pulp/paper mills), a few companies (including Chemrec AB Inc.,[13] and the Chinese Academy of Sciences, Guangzhou Energy Inst., GEI[14]) have tested key technologies only at the pilot-plant scale. GEI's biomass-to-DME process has been tested at a scale of about 3 tons/day DME (requiring the gasification of ~20 tons/day biomass).
- Various novel concepts, for the production of bio/synthetic DME, are briefly discussed in Appendix A. As mentioned in the Recommendations section, three of these processes merit further evaluations by PERC.
- In China, DME is already being used as a commercial LPG-supplement for home cooking applications. Various demonstration programs are also being implemented in China to use DME as (i) a diesel fuel in Compression Ignition engines and (ii) a blend fuel with LPG in Spark-ignited (SI) engines. Various studies indicate that for cooking with existing appliances, the upper limit for DME in a DME/LPG mixture is about 20% to 25 wt% DME. Limited small-scale studies have also been

conducted by specific R&D groups (including British Petroleum that owns a previously mentioned 1997 U.S. patent) for the use of 10-25% DME in LPG/DME blend fuels in SI engines. Comprehensive experimental studies would be required to introduce such blend fuels in these two key (residential and transportation fuels) markets for LPG in the U.S. The legal implications for the BP patent in using LPG/DME blends in SI engines also should be further explored.

- In the future as specific fuel-cell technologies mature, fleet applications for LPG as a transportation fuel could possibly be extended to hybrid vehicles utilizing the on-board reforming of DME to H_2 for fuel cell applications. This is because DME has a significantly lower reforming temperature (~ 150-250°C) vs. reforming temperatures > 650°C for methane, ethanol and gasoline.[30]

1.6.3 Scoping Economics for Bio/Synthetic propane and DME

- Our scoping economic estimates indicate that for biomass gasification-based DME or LPG production processes, the capital cost for a plant processing 3,000 tons/day biomass would be about $650-675 million (July 2009 $). For such plants, the cost of production (COP; at 13% ROI) of bio-DME would be about $2.43/gallon of propane equivalent (July 2009 $) with wood prices at $40/ton and electricity delivered at 8 cents/kwhr. Based on bench-scale data published by the Japan Gas Synthesis Ltd., for a 3,000 tons/day biomass-to-LPG plant, the COP would be about $2.31/gallon.
- Based on recent price trends, typical wholesale propane prices (without taxes or transportation costs) in the U.S. vary in the range of 50-80% of crude oil prices.[24] Thus, at a crude price of $100/bbl, average propane prices at a refinery gate would average $50-80/bbl ($1.19-1.90/gallon). Therefore, based on the Case-A bio-DME economic estimates, we would require approximate petroleum crude prices of about $150/bbl (propane @ 65% of crude) for such processes to be economically competitive, exclusive of government subsidy or GHG reduction credit.
- For LPG production as a byproduct in mega-scale coal-based (~23,000 tons/day feed rate) MTG plants, (Design Case C), costing about $4 billion, the COP would be about $0.85/gallon of propane (with a plant-gate sale price of gasoline at $70/bbl, July 2009 $). Note that this cost includes CCS. For such mega-scale plants to be economically attractive, we would require a petroleum crude price of about $55/bbl (propane price @ 65% of crude); however, such mega-scale plants would be very capital-intensive, and we would need a proven CCS technology (or plant locations with nearby existing CO_2 pipelines).
- The scoping economics for the production of DME plus electricity using coal gasification in moderately large-scale plants (Case D; coal feed: 3,860 tons/day, CAPEX: ~ $1.0 billion) indicate a COP for propane-equivalent DME gallon of about $1.35/gal. To be economically competitive, this design scenario would require a petroleum crude price of ~ $87/bbl (assuming propane price @ 65% of petroleum crude).

1.7 Recommendations

Our key recommendations on a business and commercialization strategy in increasing the usage of bio and synthetic-LPG/DME are:

- PERC should play a leadership role in promoting the use of bio/synthetic LPG and DME under the framework of the proposed EPA/RFS program which requires the production of about 36 billion gallons of various bio-fuels by 2022 (vs. ~9 billion gallons produced currently). These strategies can possibly include the establishment of a "Green Energy Advisory Task Force" to prioritize various programs for new R&D and industry education. If the RFS program is finally approved and implemented, it is likely that, depending on market demands, use of MTG/TIGAS type technologies could help produce significant quantities of bio-LPG (and possibly, some bio-DME) by 2022.
- As the ExxonMobil MTG technology is the only commercially proven technology to produce LPG as a byproduct from coal and natural gas, PERC should explore specific opportunities to work with

Haldor Topsoe to (i) further demonstrate the TIGAS technology and (ii) explore process options in maximizing LPG production. HTAS would lead a 4-year wood-to-gasoline DOE-sponsored demonstration program at GTI starting in 2010. Since DME is an intermediate in the TIGAS process, PERC may evaluate potential options, possibly to include the production of DME at this GTI/HTAS facility at a later stage of this 4-year program.

- PERC should arrange specific seminars, especially through a workshop format, to identify prospective stakeholders and organizations who would be motivated to commercialize economically attractive bio/synthetic propane and DME production technologies and new applications for LPG and LPG/DME blends. A few key examples of such firms and groups are: Haldor Topsoe, UPM, Andritz/Carbona, Virent Energy Systems Inc., LCE BioEnergy, Range Fuels Inc., Blue Fuel Inc., Chemrec AB, CleanFUEL USA Inc., and the International DME Association (a global organization involving several companies).
- PERC should extend the economic cases from this study to include (1) co-gasification of coal plus biomass, and (ii) gasification of biomass plus reforming of NG along with CCS, and (2) estimates on total lifecycle GHG emission reduction potentials for propane and DME.
- PERC should also evaluate the claims, by DieselGas Technologies Inc. of Australia,[25] that addition of some propane as a fuel in existing diesel engines would (i) enhance net BHP plus Torque, (ii) increase vehicle range, and (iii) reduce smoke emissions as well as engine wear. If these claims are confirmed, PERC should also consider evaluating the potential to use LPG/DME blends for such applications, including those for diesel-fueled fleet vehicles and distributed power generation.
- PERC should consider funding specific experimental and test marketing programs to demonstrate the use of specific LPG/DME blend fuels in existing home cooking, boilers and CHP equipments. This includes burner performance, materials of construction, indoor air quality, use of specific odorants (that may not react chemically with DME) etc.
- PERC is already quite active in promoting the public awareness and acceptance of propane as a transportation fuel in fleet vehicles. In this context, it would be helpful if basic experimental and demonstration programs, in collaboration with other firms (e.g., Alliance AutoGas of Ashville, N.C., and CleanFUEL USA of Georgetown, Texas), are funded to determine (i) safe limits for DME addition, and (ii) emission benefits for using LPG/DME blends in such transportation applications using existing SI engines.
- PERC should explore collaborative opportunities with specific U.S. R&D organizations, DOE, and private firms to further evaluate and demonstrate four key technologies for the production of LPG: (1) the BioForming process (from Virent Energy Systems Inc.) for the production of LPG from biomass[15]; (2) the process being developed by the Japan Gas Synthesis Company Ltd. for the production of LPG from synthesis gas[17]; (3) the University of Kitakyushu[18] process for the production of LPG from DME; and (4) the GTI IH^2 process for the production of LPG as a byproduct from biomass.[19]
- Similarly, in the DME arena, PERC should further evaluate the economic viability of: (1) the Isis Innovation process[20] to convert glycerol (from biodiesel plants) to DME using H_2; (2) the GTI POGT process to produce bio-DME from landfill gas or other biogas resources; and (3) the process currently being commercialized by the Carbon Recycling International Inc.[21] to produce methanol/DME from low-cost hydrogen (e.g., hydropower and wind turbines) and CO_2.
- GTI should also work with PERC and other industrial partners (e.g., Caterpillar, Siemens or Pratt-Whitney) to further develop the GTI POGT technology for the production of (i) hydrogen from propane for fuel-cell applications, (ii) DME from biogas (e.g., landfill gas), and (iii) hydrogen from glycerol (or biogas) for specific applications, such as the Isis Innovation process for making bio-DME from glycerol.
- Similarly, GTI should assist PERC in evaluating the commercial potential of the Carbon Recycling International Inc. technology to produce methanol (for conversion to DME) from low-cost hydrogen

and waste carbon dioxide. For specific locations, the GTI POGT process could potentially be useful to produce H_2 from biogas and glycerol for this CRI process.

- PERC should further evaluate the World LP Gas Association concept for integrating key renewable energies (e.g., solar) with LPG/DME-fueled systems in stand-alone systems in rural areas. This may also include reforming of DME (with air) to produce H_2 for fuel-cell applications.

2 Introduction

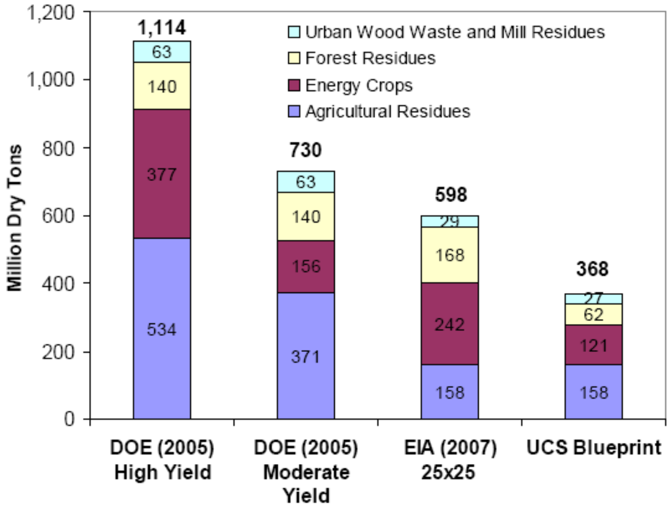
With the current emphasis on energy independence and concerns for climate change due to the use of fossil fuels (such as, conventional LPG supplies from natural gas processing and petroleum refining), the production of renewable and synthetic fuels (with CO_2 recovery plus sequestration; key literature data on GHG emissions shown in Figure 4[8]) is receiving significant attention from private industries and government agencies. The primary objectives of this study, sponsored by the Propane Education and Research Council (PERC), are:

- Task 1: Investigate and evaluate possible methods to produce synthetic propane and DME (Dimethyl Ether) from coal, wood and bio-crude oil (e.g., oil extracted from crops such as various vegetable oils).
- Task 2: Determine the economic viability, including capital/operating costs data and wholesale cost of production ($/bbl, based on July 2009 $) for the technically attractive propane and DME production technologies.
- Task 3: Based on the technical and economic viability, (i) recommend a strategy for a full-scale commercial production of synthetic propane and synthetic DME and (ii) assess conditions that would lead to industry interest in synthetic propane as well as synthetic DME (as a supplement to propane).
- Task 4: Identify major risks and uncertainty for the relevant technologies, and provide guidance on new technology requirements.
    - Analyze current key government programs related to synthetic propane and synthetic DME, and recommend potential partners for PERC in moving forward with commercialization plans for synthetic propane and DME.

2.1 Bio-energy Potential in the U.S.

CO_2 released in the ultimate combustion of bio-fuels is offset by the CO_2 extracted from the atmosphere during photosynthesis. Therefore minimizing greenhouse gases (GHG) (primarily CO_2), by maximizing various biomass resources (grown on a sustainable basis) for the production of key liquid fuels (plus electricity) would be very important. Historically, the biomass primarily used for liquid fuels in the U.S. has been corn (converted mostly to ethanol). However, due to severe concerns about effects on food prices, especially for food exports to developing countries using such biomass resources, the current emphasis on bio-fuel production is to use non-food feedstocks that are not grown as dedicated energy crops on cropland – but, primarily on degraded lands.

Various studies indicate the total annual bio-energy potential in the U.S. is in the range of about 350 million tons to about one billion tons (see Figure 1).[31,32] As an example, at a total availability of 500 million tons and 100% utilization, the U.S. can produce about 2.0 million barrels/day (MMBPD) of bio-crude. Of this total, 5-20%, or ~ 1,500-6,000 million gallons/year, could potentially be bio-propane produced through biomass gasification or synthesis gas conversion technologies currently being developed by several companies. As a perspective, during 2008, the total transportation fuel consumption in the U.S. was about 13 MMBPD, and odorized propane consumption was about 10,000 million gallons.



Sources: DOE and USDA 2005, and EIA 2007.
Note: EIA 25x25 and our Climate 2030 Blueprint numbers reflect supplies from the year 2030 at $5.25 (2005$)/MMBtu.

Figure 1 Estimates on Bioenergy Potential in the U.S.
Ref. [31, 32]

2.1.1 Potential for Bio-LPG Production per Year in the U.S. during 2022

If specific regulations for the introduction of significant quantities of bio-fuels are implemented in near future (e.g., the proposed EPA RFS program on novel renewable fuels), significant quantities of bio-LPG, and possibly some bio-DME, may be introduced in the U.S. energy markets during the next five to ten years. As an example, under the EPA RFS program, if about 15% of the required 36 Bgal of renewable fuel per year by 2022 is produced from woody biomass by TIGAS/MTG-type processes, the U.S. could produce approximately 300-1,100 million gallons of propane per year (at 5-20% of gasoline volumes - see Table 2) depending on market demands.

Table 2 Potential for bio-LPG production during 2022 under the EPA/RFS program

	Million Gallons/year	Total woody biomass need per year, Million metric tons
Total gasoline production	5,400	88[a]
Total LPG production at 5% level, at 20% level,	 270 1,100	

(a) Total Bioenergy Potential in the U.S.: 350-1,000 million metric tons/year
(b) Assumes 15% of the Required 36 Bgal of Renewable Fuel would be made via MTG/TIGAS Type Processes

2.2 Use of DME as a LPG Supplement

As DME is currently attracting worldwide attention as a supplement (or alternative) for LPG, diesel, and also as an alternative for LNG, we have included key discussions for the (i) use of DME as a LPG supplement in a few applications, and (ii) production of synthetic DME and bio-DME. Key properties of propane, butane and DME are compared in Table 3[26]:

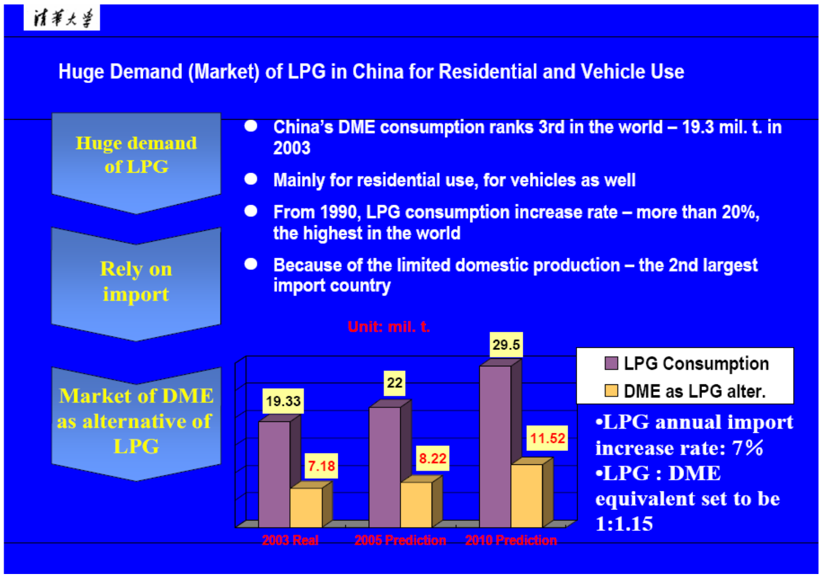
Table 3 Key Comparative Properties of Propane, DME and Butane

	Propane	DME	Butane
Chemical formula	C_3H_8	CH_3OCH_3	C_4H_{10}
Normal Boiling Point, °C	-42.0	-25.1	-0.5
Liquid Density, gm/cc, 20°C	0.49	0.67	0.57
Specific Gravity of Gas (vs. air)	1.52	1.59	2.00
Ignition Point, °C	470	235	430
Explosion Limit, %	2.1-9.4	3.4-17	1.9-8.4
Cetane Number	5	55-60	10
Octane Number	100	13	
Lower Heating Value, Kcal/kg	11,100	6,900	10,930

Ref. [26]

2.3 DME Production in China

As indicated in Figure 2, China is planning for massive investments in advancing the use of DME as a commercial fuel in multiple applications.[14, 36] Based on some reports, China intends to invest more than U.S. $128 billion to develop coal-based synthetic fuels projects by 2020. These projects aim to produce 30 million tons of (about 600,000 BPD) of coal liquids and 20 million tons of DME by 2020.[37] In Figure 2, the reference to "China's DME consumption ranks 3rd in the world – 19.3 million tons in 2003" should correspond to "LPG consumption" (not DME). Referring to Figure 2, we are unsure about the definition of the statement "LPG: DME equivalent set to be 1:1.15". Based on an October 2009 publication, the total DME production capacity in China had reached about 7 million tons by the end of 2009.[14] However, it appears that due to recent slippages in LPG demands, some of these DME plants are being operated at low operating factors of less than 50% (Table: B-3).[14]



Huge Demand (Market) of LPG in China for Residential and Vehicle Use

Huge demand of LPG

Rely on import

Market of DME as alternative of LPG

- China's DME consumption ranks 3rd in the world – 19.3 mil. t. in 2003
- Mainly for residential use, for vehicles as well
- From 1990, LPG consumption increase rate – more than 20%, the highest in the world
- Because of the limited domestic production – the 2nd largest import country

•LPG annual import increase rate: 7%

•LPG : DME equivalent set to be 1:1.15

Figure 2 Estimates on DME Production in China

Ref. [36]

2.4 *Importance of Co-processing of Biomass plus Coal for Limiting GHG Emissions: Key Literature Data*

Typically, based on LCA (life cycle analysis) for GHG emissions, Figure 3 shows that synthetic liquid fuels from coal produce substantially more CO_2 than petroleum-based gasoline or diesel fuels. Also, with Carbon Capture & Sequestration (CCS), coal-based fuels' CO_2 footprints can be roughly equivalent to petroleum gasoline.[8] However, as shown in Figure 4 for specific examples provided in the literature, synthesis of Fischer-Tropsch (FT) diesel via biomass gasification with CCS has a negative CO_2 footprint relative to petroleum fuels, and co-gasification of coal (at 58 wt%) and biomass (42 wt%) for either FT diesel or gasoline results in net "negative" CO_2 footprints.[8]

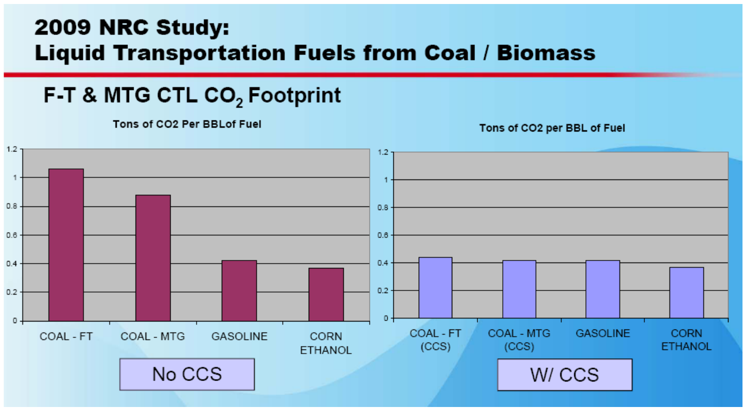


Figure 3 Literature Data on GHG Emissions for Liquids Production via Coal Gasification
Ref. [8]

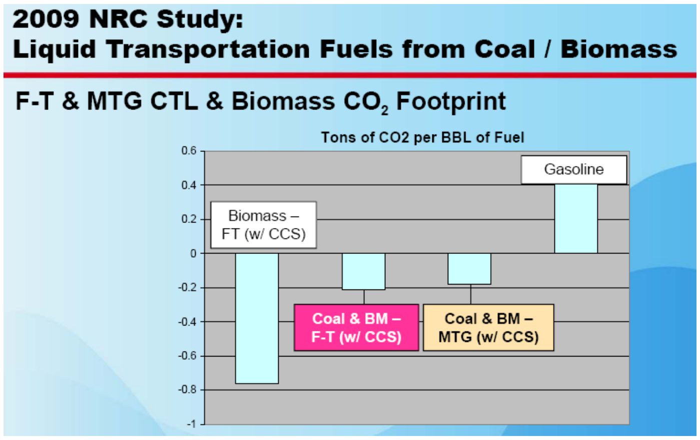


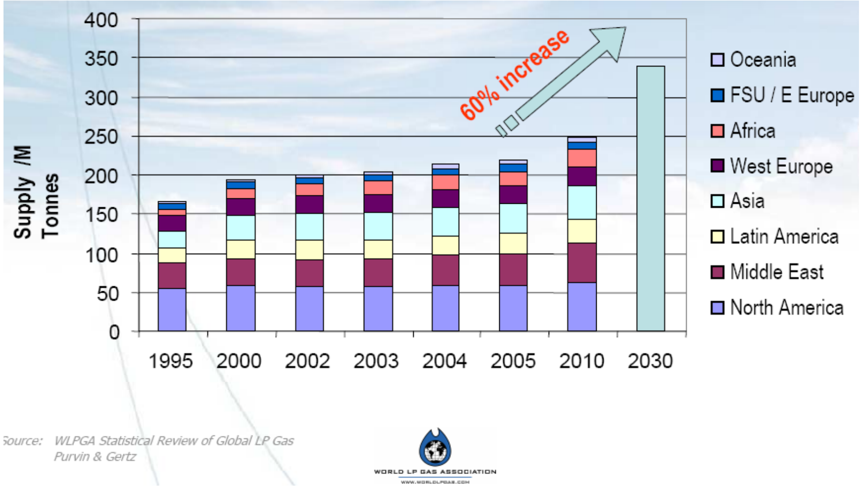
Figure 4 Literature Data on the Reduction of GHG Emissions for Liquids Production through Co-gasification of Coal plus Biomass
Ref. [8]

If proposals like the EPA/RFS for introduction of bio-fuels get implemented in the U.S., it is likely some of the MTG/TIGAS type bio-gasoline production units may co-process biomass and coal (or natural gas).

2.5 *Current LPG Consumption in the U.S.*

As shown in Figure 5, the current annual total LPG consumption in North America is about 60 million tons (vs. about 250 million tons total globally). By 2012, this is projected to increase to about 65 million ton (Appendix Figure B-8). The specific demands of LPG during 2004 in the U.S. for various sectors is given in Table 4.[38] As shown in Figure 6, based on a PERC-sponsored study by ICF International, the total consumption of odorized propane during 2008 in the U.S. was about 10,000 million gallons (about 18.5 million metric tons). According to the World LP Gas Association (WLPGA), relative to the year 2008 supplies, the total global consumption is expected to increase by approximately 35%$^+$ by 2030 (to a level of ~ 340-350 million tons per year; Figure 5).[3,5] In this context, an important issue will be the expected growth in DME production; the WLPGA estimates that by 2020, the worldwide DME production could reach 70 MM tons.[3] These supply projections indicate that there could be severe negative market price implications for both of these products, unless new novel applications are pursued (and developed) for both LPG, DME and LPG/DME blends.

As the debate on climate change issues intensifies, there would be increasing pressures worldwide to meet a certain fraction of these LPG (and DME) supplies from renewable resources, such as from biomass and co-processing of NG/coal with biomass. In addition, if world petroleum prices increase to relatively higher levels, several countries (e.g., China, U.S., India) would possibly try to produce significant quantities of specific transportation fuels (including gasoline and diesel) from coal or natural gas. For a few of these coal-to-liquid fuels technologies, such as the ExxonMobil MTG (methanol-to-gasoline) and Haldor Topsoe TIGAS (Topsoe Integrated Gasoline Synthesis) processes, LPG would be a key byproduct (at about 10-30% levels). Such future coal-to-liquids plants would also attempt to capture and sequester relatively large quantities of CO_2. Similarly, as the use of DME, which can be produced from natural gas, coal, petroleum coke or biomass, as a multipurpose fuel is attracting key attention in several countries, its use as a LPG supplement or alternative may possibly grow substantially.



Source: WLPGA Statistical Review of Global LP Gas
Purvin & Gertz

Figure 5 World LP Gas Association Projections on Global & U.S. Production of LPG

Ref. [6]

Table 4 LPG Consumption in Various U.S. Sectors During 2004

Sector Demand, Thousand Metric Tonnes	Fuel	Feedstock	Total
Residential	14,843	0	14,843
Agricultural	2,425	0	2,425
Industrial	3,929	31,180	35,109
Transport	740	0	740
Total	21,937	31,180	53,117

Ref. [38]

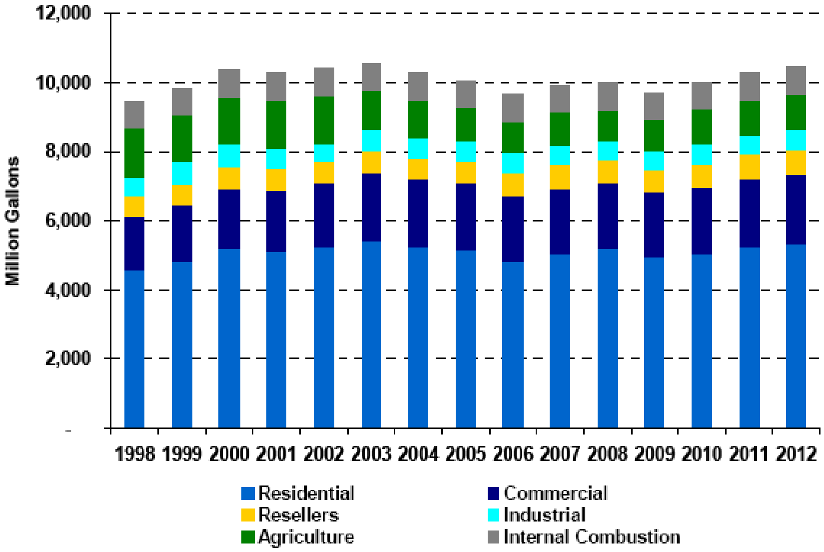


Figure 6 Near-Term Odorized-Propane Demand Forecast for the U.S.
Ref. [27]

2.6 A Potential New Market for LPG as a Supplement in Improving Performance of Existing Diesel Engines

DieselGas Technologies Inc.(DGT) of Australia has claimed that they have developed a on-board computer-assisted propane injection system for existing diesel engines that could significantly improve overall engine performance, including increases in average BHP/Torque plus vehicle range, and reductions in smoke emissions and engine wear; typical data are shown in Figure 7.[25] The key technical claim is that the efficiency rate in a typical diesel engine is about 75-80%, with the remainder of the diesel burned at times that does not produce power; with the use of DGT's "DieselGas Sequent System", the efficiency rate can potentially be increased to 95-98%. Typically, for diesel-fueled vehicles, the use of LPG can be about 20-30% of total volume of fuel used and power/torque output plus vehicle range can be increased by about 20%; for current economic scenario in Australia, the company claims that the use of propane would reduce typical fuel costs for diesel-fueled vehicles by about 20%[+]. For applications with stationary diesel engines, the propane addition can possibly be increased to 35-40% of the total volume of fuel used. This technology could possibly be also used for LPG/DME blends.

Other investigators have also demonstrated the use of LPG/DME blends in diesel engines.[39]

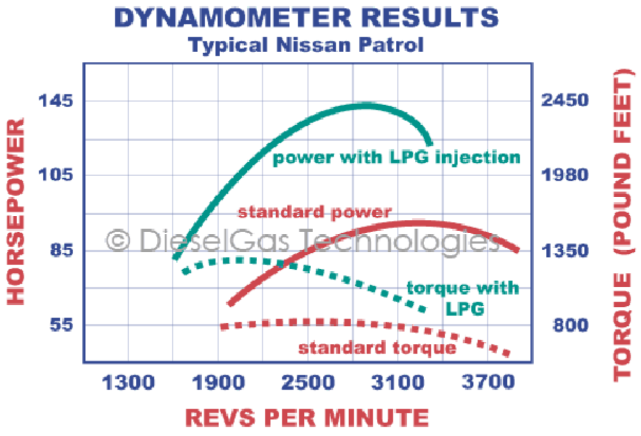


Figure 7 Use of LPG to Enhance Performance of Existing Diesel Engines (Claims by DieselGas Technologies Inc.)

Ref. [25]

2.7 Use of DME as a LPG Supplement

Currently, DME (made mostly via methanol dehydration) is used commercially as an aerosol spray propellant. Multiple studies, including those by Du Pont, have shown that DME is benign, has low toxicity, and is non-carcinogenic. For the U.S. markets, other applications can potentially be developed especially if crude petroleum prices remain relatively high (e.g., greater than $80/Bbl, 2009 dollars). PERC could consider promoting the following applications, especially for using Green LPG (bio-LPG; made as a byproduct, with gasoline as a major product, from biomass) and Green DME (from biomass).

2.7.1 DME as a LPG Supplement for Home Cooking and Heating Applications

For DME market penetration and end-user acceptance (especially for Green DME made from biomass), DME can be used initially as a LPG supplement at about 15-20 vol. % levels for domestic cooking and heating applications. As shown in Figure 8, studies by Snamprogetti (a subsidiary of the ENI Group)[3] indicate that for existing home cooking appliances, use of 15-20 volume% of DME in LPG/DME blends would not require any modification of existing distribution process and user’s appliances. This has been confirmed by other researchers.[26,40] Figure B-9 (Appendix B) provides typical schemes and guidelines that are being pursued in China for converting existing LPG distribution infrastructures to use LPG/DME blends.[14]

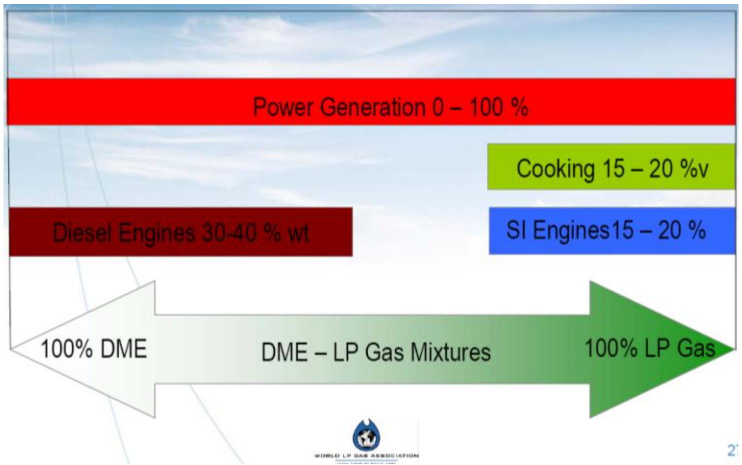


Figure 8 Projections by Snamprogetti Inc. for Safe DME Levels in Home-Cooking & SI Engine Applications for LPG/DME Blends without Modification of Existing Distribution Process & Users Appliances.

Ref. [3]

The LPG industry would require additional experimental studies to determine the safe limits for DME in LPG/DME blends as a prerequisite to commercialization of such LPG/DME blends for home cooking, heating or transportation applications in the U.S. using existing appliances or vehicles. These studies should evaluate key performance parameters including burner performance, materials of construction, use of conventional seals/gaskets, use of specific odorants that are currently used for propane, and indoor air quality. An important factor that must be carefully evaluated is the setting of specific standards for future commercially-produced DME fuels that may contain various impurities including methanol, higher alcohols and traces of water.

2.7.2 *Use of LPG/DME Blends Fuels for Fleet Vehicles*

In the U.S., LPG is the leading alternative fuel; it is also the third most common vehicular fuel today, after gasoline and diesel. Over 270,000 on-road vehicles in the U.S. (vs. more than 10 million worldwide) operate on LPG. A large number of these are used in fleets that include light-to heavy-duty trucks, buses, taxicabs and police/rental/delivery vehicles. However, there are indications that LPG is facing severe competition in this market due to competing fuels (e.g., hybrid vehicles) and new stricter emission regulations.[27]

As shown below in Table 5, uses of propane in such fleet applications have key emission reduction advantages over gasoline. These data reflect vehicle GHG emissions only, and not those for entire life-cycle type GHG comparisons.

Table 5 Relative Emission Comparison in Fleet Applications - Gasoline vs. Propane

GHG components	Relative Emission for Gasoline	Relative Emission for Propane
CO	100	40
CO_2	100	88
NO_x	100	80
Key toxins, e.g., Benzene & Toluene	100	~4

Ref.: Butane Propane News, October 2009

Preliminary research at BP (U.S. patent # 5632786, issued May 27th, 1997) indicated that, although DME is primarily a fuel with a high Cetane Number (and thereby, an excellent diesel fuel), a DME/Propane blend of about 10-25 wt% DME can be used in specific SI engines (suitable for gasoline or LPG type fuels) due to the relatively high Octane Numbers for LPG fuels. Various other studies have also indicated similar potential for DME/LPG blends. The BP patent claims that a DME/Propane blend fuel containing about 10-25 wt% DME can be used in specific SI engines. The patent provides key data (shown in Table 6) on RON (Research Octane Number) and MON (Motor Octane Number) for various LPG/DME blends.

Table 6 Key Properties of Propane vs. Various Propane/DME Blends

Wt.% DME	0	10	15	20	25
Wt% Propane	100	90	85	80	75
RON	111.5	103.9	100.1	96.3	92.5
MON	100	91.3	86.9	82.6	78.2
(R+M)/2	106	97.6	93.5	89.5	85.4
Vapor Pressure @ 30 °F (psig)	262	253	248	244	239

Ref. BP U.S. Patent # 5632786

According to this patent, a 1988 Buick Century automobile with a 3.8 liter engine (originally manufactured to utilize gasoline as a fuel) was modified to run on (i) 100% propane and (ii) a blend with 19 wt% DME and 81 wt. % propane. The emission data indicated (i) reduced CO emission for the DME/Propane blend: 3.406 gm per mile (vs. 5.664 gm/mile for 100% propane), and (ii) reduced total hydrocarbons for the DME/propane blend: 0.461 gm/mile (vs. 0.532 for 100% propane).

A study by Lee et al also concluded that blended DME/LPG fuel containing up to 10 wt% DME can be used as an alternative to LPG for SI engines.[29] In this study, however, 100% n-butane (with no propane content) was used as a LPG fuel.

2.7.3 Use of DME as a Hydrogen-carrier

As fuel cell technologies mature, it should be possible to consider the use hybrid power systems involving on-board reforming of DME (especially bio-DME), which requires relatively low temperatures (e.g., 150-250°C vs. 650°C for methane, ethanol and gasoline) for reforming to H_2 with air/steam, for such LPG/DME fueled fleet vehicles. Studies have demonstrated that DME and methanol (which, unlike DME, has some toxicity issues) are clear favorites in such on-board fuel cell applications in terms of fuel processor mass/volume and overall drive efficiency.[30]

2.7.4 Use of LPG/DME Blends in Forklifts

Propane is currently used in certain types of forklifts that have internal combustion engines with (i) either solid tires (Class 4 forklifts) and (ii) with pneumatic tires (Class 5). Additional R&D work would be needed to determine suitable levels of DME in the DME/LPG bend fuel that can be used safely in these applications.

2.7.5 LPG/DME Fuel Partnering with Renewable Energy to Use

LPG/DME as a fuel partner with renewable energy can be part of stand-alone integrated systems, consisting of solar panels, electricity storage battery units, DC/AC inverters and DME/LPG blend-fueled CHP (combined heat and power) generators, in meeting all the energy needs of families in rural areas.[6]

The World LPG Gas association is currently promoting such systems (see Figure B-1) for developing countries. PERC may evaluate the market potential for such systems, especially using Green LPG or Green DME made from biomass resources. An important aspect to consider in this context is that DME can be reformed to H_2 (using steam) at relatively low temperatures (~150-250°C; vs. greater than 650°C for methane, ethanol and gasoline). Therefore, it should be possible to extend this concept of LPG/DME fuel partnering (especially using bio-DME) with renewable energy to include DME-powered fuel cells for efficient generation of electricity in these types of stand-alone systems.

3 Task 1.0 Review of Specific Processes and Methods for the Production of Synthetic LPG and DME

3.1 Near-term Technologies

The ExxonMobil MTG technology is a key commercially proven technology to produce LPG (as a byproduct only, with gasoline as the primary product) from coal or natural gas. JAMG Inc. of Shanxi, China, has started up a 2,500 bbl/day MTG plant in 2009.[8] Haldor Topsoe (HTAS) is also developing a competing process (the TIGAS process, demonstrated at a scale of 5 bbl/day only) to produce gasoline plus LPG from natural gas, coal or biomass. Specific details on the MTG technology are given in Appendix A. For other technologies such as Fischer-Tropsch diesel, the yields of LPG components are relatively smaller.

- Several companies (e.g., Toyo Engineering, HTAS, Lurgi) have developed DME synthesis technologies to utilize coal or natural gas. Toyo has already built four coal-based commercial plants in China. Figure A-4 shows a process flow diagram for the Toyo process.
    - For biomass gasification, the ExxonMobil MTG process or the TIGAS technology would very likely be commercialized within the next three to five years. For air-blown gasification of biomass in power generation applications, GTI's biomass gasification technology has already been commercialized by Andritz/Carbona Inc. Several companies are developing oxygen-blown biomass gasification systems, usually preferred for liquids production; e.g., GTI is currently demonstrating its technology with UPM/Andritz-Carbona at a scale of 20 tons/day.
    - DME can also be made from syngas derived from oxygen/air/steam based gasification of biomass including black liquor from paper/pulp mills. A team led by Chemrec, Volvo and HTAS are now building a 5 tons/day DME plant in Sweden to utilize black liquor.[13]
    - The Chinese Academy of Sciences is also operating a pilot plant to produce ~ 3 tons/day DME via biomass gasification (at ~21 tons/day feed rate).[14]

3.2 Other Potential Concepts/Technologies Requiring Significant Additional R&D and Demonstration

Specific novel concepts, mostly demonstrated under bench-scale research, for production of synthetic LPG are discussed in Appendix A. These concepts require significant R&D expenses before they could be ready for commercialization. Depending on the R&D resources, we recommend that PERC especially monitor and evaluate seven of these process concepts.

3.2.1 For Synthesis of LPG

- The Bioreforming Process is currently being developed by VIRENT Energy Systems (VES) Inc.: VES has developed the Bioreforming process for the production of renewable liquid fuels from biomass feedstock. According to VES, plant sugars can be converted into specific liquid fuels like gasoline or diesel, including LPG, by their patented aqueous-phase reforming technology. VES has formed a joint venture (JV) company with Shell for the production of gasoline and diesel type fuels from biomass.
- The Japan Gas Synthesis Co. Ltd. (JGS) process for direct synthesis of propane and butanes from NG/coal and biomass-derived syngas,
- The University of Kitakyushu process for the conversion of DME to LPG.

- The GTI IH^2 process in which LPG would be produced as a by-product (with gasoline plus diesel as the major products).

3.2.2 For Synthesis of DME

- The Isis Innovation process to convert glycerol (a byproduct in bio-diesel production processes) plus hydrogen to methanol which can be further converted to DME.[20]
- The GTI POGT (Partial Oxidation Gas Turbine) process for the (i) production of DME from biogas or landfill gas, or (ii) for the production of H_2 from biogas.
- The process currently being commercialized by Carbon Recycling International to produce methanol (and then DME) from low-cost hydrogen and waste CO_2.[21]

3.3 A Few Specific Details on these Novel Concepts (Discussed in Appendix A)

- The Bioreforming Process is currently being developed by VIRENT Energy Systems (VES) Inc.: VES has developed the Bioreforming process for the production of renewable liquid fuels from biomass feedstock. According to VES, plant sugars can be converted into specific liquid fuels like gasoline or diesel, including LPG, by their patented aqueous-phase reforming technology. VES has formed a JV company with Shell for the production of gasoline and diesel type fuels from biomass. According to Mr. Larry Osgood, President of Consulting Solutions LLC, the VES process was initially developed to produce primarily LPG. However, the R&D program was then modified under the guidance of DOE to primarily produce gasoline plus diesel range liquids.
- Direct Synthesis of LPG from synthesis gas. A process is currently being developed by the Japan Gas Synthesis Co. LTD in cooperation with the University of Kitakyushu, Japan. This process has been demonstrated at a scale of only 1 kg/day of LPG.
- Conversion of DME into LPG via hydrogenation. The basic research has been conducted by Prof. Kenji Asami et al at the University of Kitakyushu. If this process can be demonstrated at a relatively high scale, this would allow a semi-indirect synthesis of LPG (via the DME intermediate) from NG/coal or biomass-derived synthesis gas.
- Production of DME using hydrogen (preferably derived from water electrolysis using cheap electricity if available, for example, from hydropower or wind turbines) and CO_2. This concept is currently being developed by Blue Fuel Energy Inc. of British Columbia, Canada[41] and others. While CO_2 has been used, in conjunction with H_2 + CO, in conventional methanol plants using natural gas as a feedstock, several firms (e.g., Mitsui Chemical, Japan[42] and Carbon Recycling International of Iceland[21]) are currently working to develop efficient catalyst systems to produce methanol from H_2 and CO_2 only. Methanol can be dehydrated to produce DME. Such process schemes would be strongly depended on the availability of cheap electricity (e.g., from hydropower or wind) for the production of H_2 from water, or reforming of low-cost glycerol (a byproduct from biodiesel plants) or biogas to make H_2.
- GTI's POGT (Partial Oxidation Gas Turbine) technology for the production of DME from landfill gas or other biogas resources. This technology has been demonstrated at a scale of 250 kW for the production of synthesis gas from natural gas using air plus steam. Additional R&D work would be needed, especially in partnership with a gas turbine manufacturer, to extend the concept to the use of oxygen and enriched-air.
- Production of bio-methanol and bio-DME from Glycerol (Isis Innovation Process).[20] Glycerol is a major byproduct in biodiesel production from various vegetable oils (e.g., corn oil). In the Isis Innovation process (developed at the University of Oxford), glycerol and hydrogen are converted to methanol via catalytic hydrogenolysis. In the future, this process could be useful if low-cost oil can be produced from algae. However, this process would still require hydrogen which, depending on the

overall costs, could be produced from water (via electrolysis), or from biogas, or a part of algae-based oil could be reformed to produce H_2.

- GTI's IH² process involves integrated hydropyrolysis (in the presence of hydrogen and suitable catalysts) and catalytic hydro-conversion of biomass to produce fungible gasoline and diesel fuel (or blending components) directly. Vapors from the first pyrolysis step would pass directly to the second-stage hydro-conversion reactor where a hydro-de-oxygenation catalyst removes all remaining oxygen and produces gasoline and diesel range materials. In this process, some LPG (about 10 % or less) would be produced as a byproduct.
- Bio-propane from vegetable oils and other related resources (concept proposed by the Mississippi State University (MSU)). Prof. M. G. White and Prof. R. Hernandez of MSU have proposed a process for the production of Bio-LPG via catalytic cracking of acyl glycerides (AG), the primary components of (i) microorganisms that can be grown using wastewater treatment infrastructure, (ii) vegetable oils (currently used for the production of biodiesel) and (iii) animal fats. Catalytic cracking is a well-established technology in the petroleum industry. However, based on the published data from MSU, the yields of the total gaseous components (including LPG fractions) are relatively low at only about 10-20 wt%. This concept in using the available petroleum refinery infrastructures would be viable for vegetable oil resources available within a relatively short distance from a refinery. Importantly, due to the ongoing concerns for the use of vegetable oil derived from food resources, most of the available vegetable oil in the U.S. would be used locally for biodiesel production that could be more cost-effective relatively to the added transportation costs in bringing such oils to an existing refinery. This concept, however, could be attractive if the production of low-cost algae is commercialized in the future.
- Conversion of fine carbon powder to propane using proprietary electrolytic technology (claims by Cato Research Corporation (CRC) of Golden, Colorado).[43] CRC has claimed that propane can be produced from specific active carbon fines (called "Cato Carbon") which can be produced from various raw materials including biomass, coal or waste rubber. CRC has demonstrated the proof-of-concept for the production of fine powder from coal and biomass. However, they have not yet demonstrated the so-called "electrolytic" step for the production of propane from fine carbon powder.

4 Task 2.0 Scoping Economics

As shown in Table 7, we have developed four scoping economic cases for the production of LPG and DME from either biomass or coal:

Table 7 Scoping Economic Cases Analyzed in this Study

Scoping Economic Case	A	B	C	D
Primary Products	Coproduction of DME plus Electricity using Biomass Gasification	Coproduce Propane plus Electricity using Biomass Gasification (Modification of Case A)	Mega-scale Plant Coproduce Gasoline, Propane and Electricity using Coal Gasification	Moderate Scale Plant Coproduce DME plus Electricity using Coal Gasification
Gasification Technology	GTI	GTI	Generic	GE
- Liquid Production	Air Products & Chemicals (APCI)	Basic R&D: Japan Gas Synthesis Ltd.	ExxonMobil MTG	APCI
Biomass or Coal Feed Rate , metric tons/day	3,000 (wood)	3,000 (wood)	23,200 (coal)	3,859 (Coal)
Propane Production (DME Equivalent), Millions gallons/yr (90% plant capacity)	69.3 (DME : 630 metric tons/day)	69.3	114.60 (plus *44,000 bbl/day of gasoline)*	118.94 (DME: 1,080 metric tons/day)
Net Sale of Electric Power, MW	26.3	26.3	111	172.8
CO_2 Capture	Yes [a]	Yes[a]	Yes[b]	Yes[a]
CO_2 Compression to 2,000 psig[c]	No[c]	No[c]	Yes	Yes[c]

(a) Partial CO_2 Capture only (not for electric power generation); costs for sequestration not included, (b) Costs for CO_2 capture plus sequestration included; (c) No credit for any CO_2 sale

The primary feedstock, products and key technologies for these four Scoping Economic Cases are:

- Case A (key details are given in Appendix C) was developed to determine scoping economics for the production of green DME via oxygen-blown gasification of biomass. Material and energy balances for the (i) gasifier section have been developed using GTI's internal fluidized bed, biomass gasification data, and (ii) those for the DME plant are based on APCI data[44] (see Table C-3 in Appendix C), and the Rectisol Acid Gas Removal step were developed using the data published by Kreutz et al[45] Capital cost data for the gasifier section and those for the DME plant and the AGR unit are based on the data from Kreutz et al.
- For Case B (key details are given in Appendix D), we modified Case A to determine scoping economics for the production of green propane from biomass (key catalyst systems are currently being developed by Japan Gas Synthesis Ltd.). For the material/energy balances for the plant, we assumed that the (i) propane yield would be the same on the energy-equivalent basis for the DME production in Case A, and (ii) the net electricity production was modified by assuming that the LPG

process would require lower reactor operating pressure (800 psia) vs. about 1,265 psia for the DME reactor.

- Case C (key details are given in Appendix E) was developed based on a recent publication from ExxonMobil[8] on scoping economics for mega-scale plants (with capital costs of about $4.0 billion) for the production of gasoline (plus LPG and electric power) from coal using their MTG technology. LPG is a byproduct in this process. The capital cost data reported by ExxonMobil includes the cost for carbon capture plus sequestration.
- For Case D (key details are given in Appendix F), we used literature data from a DOE/NETL publication[23] (for coproduction of liquids plus electricity using gasification of Pittsburgh #8 Coal) to determine scoping economics for the co-production of DME plus electric power from coal in a moderately large plant costing about $1.0 billion. The capital cost data for the gasifier section have been derived from the DOE report and those for the DME plant were developed from the report by Kreutz et al.[45]

The key analysis for woody biomass (Cases A and B) and Pittsburgh #8 coal (for Case D) are shown in Table C-1.

The results for the four design cases are summarized in Table 8. The key economic assumptions for these economic scenarios are:

- Cost basis: 2009 $
- EIA projections on prices for coal and electricity for the period 2015-2030 are shown in Figures B-2 and B-3. The price trends for (i) petroleum crude and wholesale LPG price trends are shown in Figures 9[46] and Figure 10[46] respectively, and in Figure B-4[27]. Recent residential prices for LPG are shown in Figure B-5.
- Base Case cost of wood at $40/metric ton dry basis and coal Price at $35/metric ton as received.
- Electricity price at $0.08/kwhr.
- 13% capital charge factor (about 13% Return on Investment: ROI) for annual capital % of Capital per year.
- Labor/utilities costs at 5% of Capital per year, Maintenance/taxes/Insurance costs at 4% of Capital per year.
- Gasoline selling price at plant gate (for Case C: $70/bbl or ~$1.67/gallon).
- We did not include any potential credit for selling near-pure CO_2 for EOR (Enhanced Oil Recovery) applications. Construction of new CO_2 pipelines is quite expensive. According to studies at the Institute of Transportation Studies, University of California, Davis,[47] a new pipeline carrying 10,000 metric tons/day of CO_2 would cost about $50 million (2009 $) for a length of 100 kilometers and $275 million for a length of 500 km. Figure B-7 shows existing CO_2 pipelines in the U.S. As a general guideline, for a CCS project with sale of 10,000 tons/day of CO_2 for EOR applications, the required selling price for CO_2 at 13% ROI would need to be about $3.50/ton for a 100 km new pipeline and $19.0/ton for a 500 km new pipeline.
- Use of the Chemical Engineering Plant Cost Index (CEPCI) to modify cost data to July 2009 dollars.

4.1 Key Scoping Economics Results

The key results for the four economic cases are summarized below in Table 8 and in Figure 11. The economic sensitivities for the prices of wood (Case A) and gasoline (Case C) are shown in Figure 12.

Table 8 Key Results for the Four Economic Cases (July 2009 $)

Economic Case	**A**	**B**	**C**	**D**
Propane production, million gallons/yr (90% Capacity)	69.32	69.32	114.60 (plus 44,000 bbl/day gasoline)	118.94
Net electric power for sale, MW	26.3	26.3	111.0	172.8
Net Thermal Efficiency, % (LHV)	45.3	46.0	52.9	53.9
Total capital need, $MM (May 2009 dollars)	672	649	4,020[a]	1,028
Base case Cost of Production (COP) of Propane (or DME as propane Equivalent gallon) at 13% ROI, $/gallon	2.43 [b]	2.31	0.85[c]	1.35

(a) Includes Carbon Capture/Sequestration, (b) If wood price is $70/ton, RSP would be $2.83/gallon of propane equivalent, (c) if gasoline selling price is $60/bbl, COP will be $1.98/gallon

Figure 9 Price Trends for Petroleum Crude, $/bbl

Ref. [46]

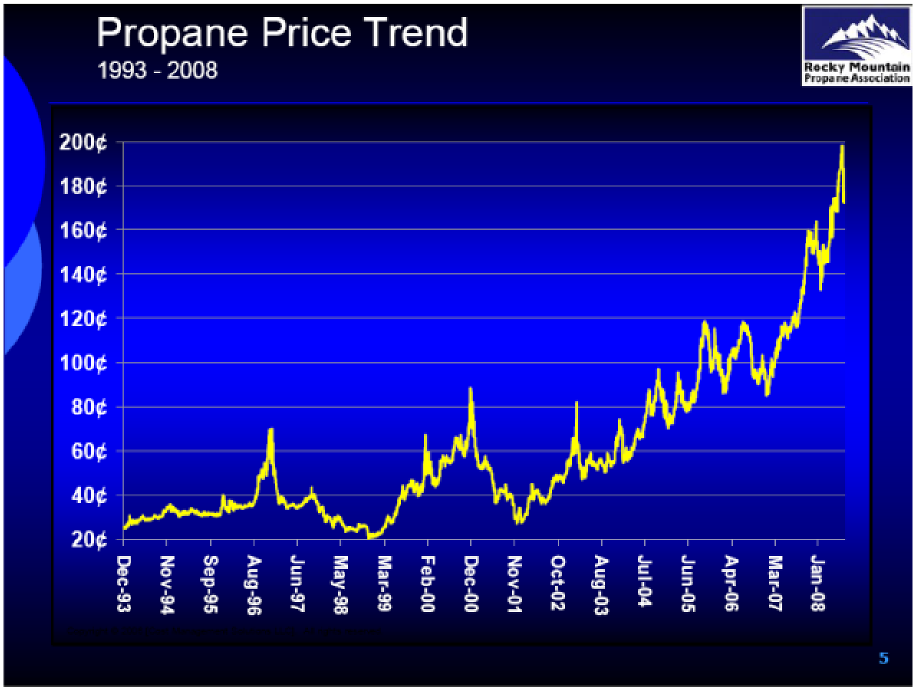


Figure 10 Wholesale Price Trend for Propane, Cents/gal
Ref. [46]

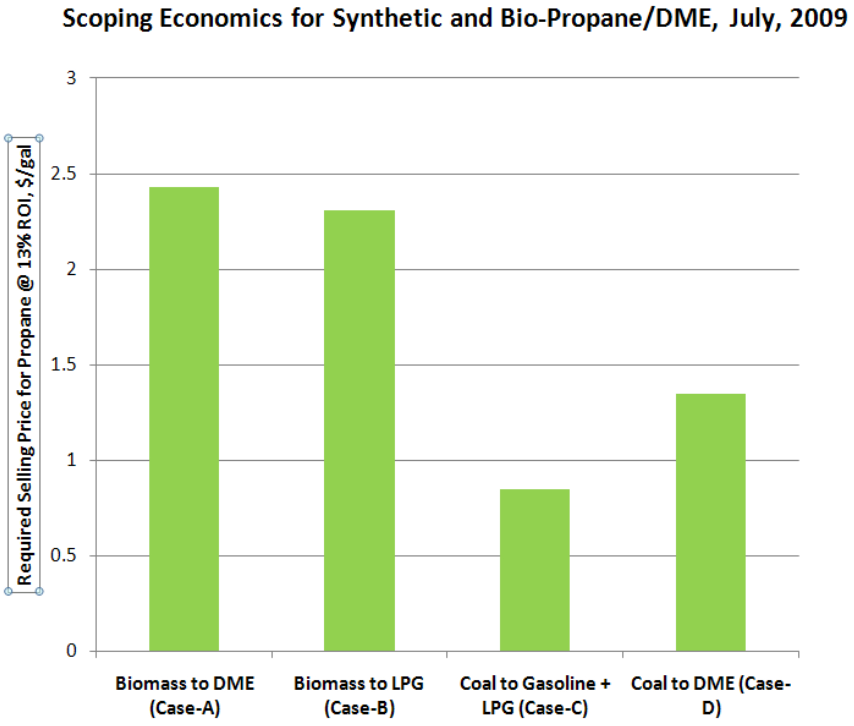


Figure 11 RSP of Propane for Various Design Cases

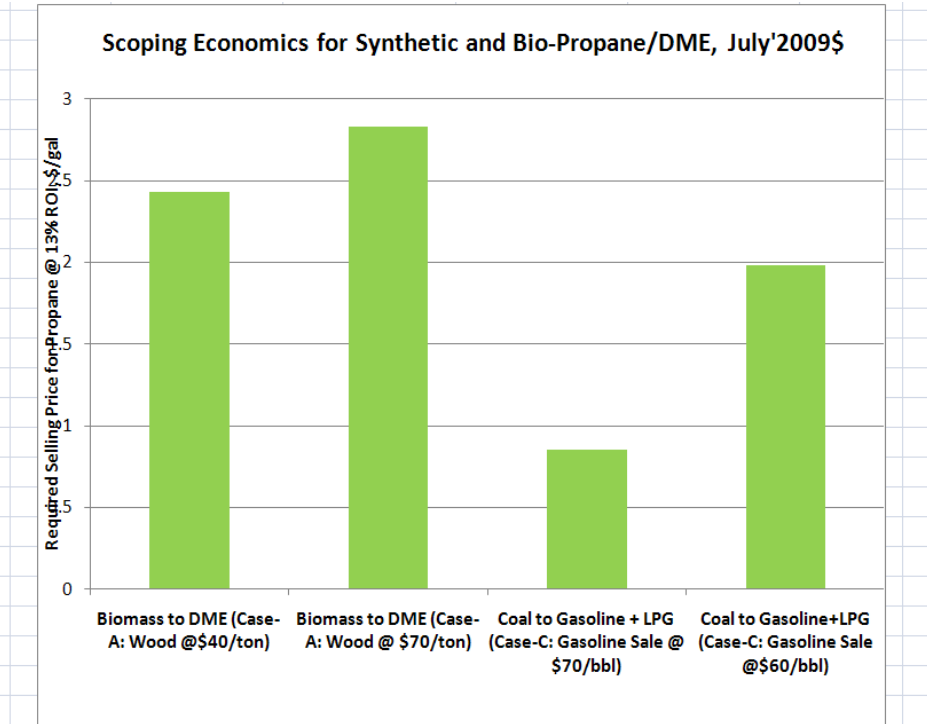


Figure 12 Economic Sensitivities for the Prices of Wood and Gasoline (Cases A and C)

5 Task 3.0 Recommendations on Key Strategies for Commercialization of Promising Options for Synthetic LPG and DME

5.1 LPG-Industry Education

Depending on the status of potential federal regulations on the future emission limits for GHG, PERC should consider playing a leadership role in promoting the usage of bio-LPG/DME and synthetic LPG/DME under the basic framework of the Energy Independence & Security Act of 2007 (especially under the proposed EPA/RFS program). This Act requires increasing bio-fuel production (primarily ethanol) from 9 billion gallons in 2008 to nearly 36 billion gallons by 2022. If approved by the Congress, such government mandated programs for introducing renewable fuels in the U.S. may also allow production of significant quantities bio-propane (and possibly, bio-DME) by 2022.

- These strategies could also include the establishment of a "Green Energy Advisory Task Force" to prioritize various programs for new R&D plus industry education, including ways to accelerate the construction of coal/Natural Gas (NG) and biomass based production facilities (e.g. using the MTG technology) to coproduce LPG/gasoline and electricity from coal/NG plus biomass.
- PERC is already quite active in promoting LPG-fueled fleet vehicles, including school buses and taxicabs. In this context, PERC should consider educating the LPG industry on (i) the basic technologies, such as the ExxonMobil MTG and the HTAS TIGAS technologies for the coproduction gasoline/LPG and DME from coal/biomass or natural gas/biogas, and (ii) importance of co-production of these fuels with electricity, using coal plus biomass or natural gas plus biomass, for the reduction of GHG relative to fossil fuel based LPG.
- Extend the economic cases developed in this study to (i) co-process coal and biomass and (ii) natural gas plus biomass, including Carbon Capture plus Sequestration. Conduct detailed site-specific economic studies, in co-operation with key (i) stakeholders like CleanFUEL USA (Georgetown, Texas), Alliance AutoGas (Ashville, N.C.) and Railroad Commission of Texas, and (ii) private firms like Haldor Topsoe, LCE Bioenergy (NY), Blue Fuel Energy Inc. of Canada, UPM (a pulp and paper company from Finland that owns a plant in Minnesota), Andritz/Carbona (a licensee of GTI's biomass gasification technology), and Carbon Recycling International (an Icelandic/American firm).

5.2 Promotion of Basic R&D

5.2.1 Development of New LPG/DME Markets

- For early market acceptance and technology demonstration, PERC should consider funding specific experimental projects to:
    a. Confirm the safe limits of DME as a supplement in LPG/DME blends (i) for applications using existing equipments for home cooking/heating, boilers and electricity generation and (ii) as a transportation fuel in SI engines (e.g., school buses and taxicabs).
    b. Develop air/steam reforming of DME to produce hydrogen for fuel-cell applications, especially for (i) stand-alone systems that integrate LPG/DME fuels with renewable energy like solar energy and (ii) hybrid fleet vehicles operating on LPG/DME blends and gasoline bi-fuels.

5.2.2 New LPG Production Processes

- PERC should consider funding suitable collaborative projects to develop the TIGAS technology (being developed by Haldor Topsoe) further as a competing technology option to the ExxonMobil MTG process for the co-production of LPG and gasoline from biomass and coal.

- Explore the potential of working with VIRENT Energy Systems (VES) Inc. and Shell to maximize the production of propane in their Bio-reforming process. According to VES, plant sugars can be converted into specific liquid fuels like gasoline or diesel, including LPG, by their patented aqueous-phase reforming technology.
- Explore ways to demonstrate, using suitable pilot-plant reactor systems, (i) the Japan Gas Synthesis Company Ltd. catalysts to produce LPG from biomass or coal-derived syngas, and (ii) University of Kitakyushu catalysts for the production of LPG from DME from biomass or coal-derived syngas.
- PERC should consider further (i) evaluating the GTI POGT technology, already proven using air and natural gas, for the production of bio-DME from biogas using oxygen and natural gas, and (ii) funding a project at GTI in collaboration with a gas turbine manufacturer, such as, Siemens, Caterpillar or Pratt-Whitney.

6 Task 4.0 Risks/Uncertainties for Relevant Technologies, New Technology R&D Requirements and Relevant Current U.S. Government Programs

6.1 Risks/Uncertainties of Relevant Technologies for the Production of Synthetic/Bio LPG and DME

6.1.1 Near-term Technologies

- The ExxonMobil MTG technology is the only commercially available process to produce synthetic LPG as a significant byproduct (with gasoline as the primary product) from coal or natural gas. Other commercial coal-to-liquids or natural gas-to-liquids processes, such as the Sasol low-temperature FT process, relatively smaller quantities of LPG as a byproduct. As oxygen-blown biomass gasification (e.g., the GTI fluidized bed process) are still under development in the U.S., it may take additional three to five years before the MTG process can be commercialized for processing biomass or co-processing biomass/coal.
- Nuon Inc. of Netherlands has conducted successful tests in co-processing coal and biomass (at about 30 wt% biomass) using the Shell gasification technology. Therefore, this Nuon/Shell team would be able to build commercial plants using coal plus biomass if they can procure a license for the MTG technology from ExxonMobil.
- The Haldor Topsoe TIGAS process for co-producing LPG (as a byproduct only at about 10-30 % level) and gasoline is currently being developed to process either biomass or coal. It was proven at only 5 bbl/day scale using natural gas as a feedstock. Therefore, it may take an additional three to five years before this technology would be ready for commercialization for utilizing natural gas, coal or biomass.
- Several technology licensors (e.g., Haldor Topsoe, Lurgi, Toyo Engineering, and Mitsubishi Inc.) can provide commercial guarantees for the production of DME from either natural gas or coal. It seems that for applications involving biomass gasification, these technologies for the coproduction of gasoline/LPG and for the production of DME would quite likely be commercialized within the next five to seven years. However, specific firms may have proprietary biomass gasification technologies that may shorten this commercialization time frame. The key technology steps that need additional demonstration include: (1) tar reforming (various tar components, such as naphthalene, are usually present at gasifier exit) and (2) extensive cleanup of syngas prior the DME/methanol synthesis step.

6.1.2 Technology Concepts that would need Significant R&D Resources

Based on our overall assessments of various novel concepts for the production of bio/synthetic propane or DME, we recommend seven specific process concepts (highlighted in the Executive Summary) for additional evaluations and potential funding by PERC. Each of these specific new concepts have R&D requirements.

1. For the VES Bioreforming process, the key objective should be to demonstrate if propane could be produced with relatively high selectivity (vs. gasoline and diesel).
2. For the Japan Gas Synthesis Ltd. concept for producing LPG from syngas, the key R&D needs are: (i) to demonstrate a suitable reactor system that can be operated on a long-term basis with catalyst integrity and activity maintenance using syngas produced from natural gas, coal or biomass, and (ii) extensive demonstration of the integrated coal/biomass gasification (or NG reforming) and the syngas-to-LPG synthesis step.
3. For the University of Kitakyushu concept for converting DME to LPG, the key R&D needs are the same as those for the preceding concept from Japan Gas Synthesis Ltd.: (i) to demonstrate a

suitable reactor system that can be operated on a long-term basis with catalyst integrity and activity maintenance using syngas produced from natural gas, coal or biomass, and (ii) extensive demonstration of the integrated coal/biomass gasification (or NG reforming) and the syngas-to-LPG synthesis step.

4. For the GTI IH[2] process, the key uncertainty is the extent of LPG production as some of these components would be used to generate hydrogen required on the process.
5. For the Isis Innovation process for the conversion of glycerol to methanol using hydrogen, we would need to establish (i) long-term stability and catalytic activity of the catalyst(s), (ii) demonstrate a suitable reactor system for continuous operation using the specific catalyst(s), and (iii) key options in supplying the H_2 required for the overall process.
6. For the GTI POGT concept for a potential biogas-to-DME process, we would primarily need to demonstrate:
    a. A suitable oxygen-based combustor, prior to the turbine section, operating at relatively high temperatures; various technologies, such as the Haldor Topsoe ATR (Auto Thermal Reformer) or the ConocoPhillips COPox™ technology for reforming methane with oxygen, can possibly be modified for this step.
    b. Long-term operation of a suitable expander (from a specific turbine manufacturer) using biogas-based syngas at relatively high temperatures.
7. The CRI (Carbon Recycling International Inc.) process to produce methanol (and thereby, DME via dehydration) directly from hydrogen and carbon dioxide is currently being demonstrated in Iceland. For that plant, the process has to demonstrate long-term stability and activity for the catalyst(s).

6.2 Current U.S. Government Programs in Promoting LPG and other Bio-fuel Projects

As part of the Energy Independence and Security Act of 2007, EPA has proposed new requirements under the Renewable Fuel Standard (RFS) program that requires increasing bio-fuel production from 9 billion gallons in 2008 to 36 billion gallons by 2022, including 21 billion gallons of advanced bio-fuels. Advanced bio-fuels are defined as “a renewable fuel other than ethanol and which must achieve a lifecycle GHG emission displacement of 50%, compared to the gasoline or diesel fuel it displaces.” Specific details of this EPA/RFS proposal are given in Tables B-1 and B-2. Several projects have recently been approved by the U.S. DOE and USDA to promote the production of various bio-fuels.[11]

As a part of the American Recovery and Reinvestment Act, the Federal Government has also agreed to spend about $33.5 million for dedicated propane projects, mostly under the U.S. DOE Clean Cities program, and other extra funds for various initiatives that include propane among other alternative fuels. A few of these programs are[48]:

- A $12.6-million Railroad Commission of Texas (RRC) project that will build 35 propane refueling stations and deploy nearly 882 propane vehicles for 40 school districts and public agencies. The initiatives includes a match of $37.7 million from the grant participants for the purchase of 245 propane school buses and 637 light- and medium-duty propane trucks, vans, and cars. The key objective is to increase public awareness and acceptance of propane as a transportation fuel.
- Another $12.3 million award has been granted to the Texas State Technical College in Waco, Texas. The project will develop 184 propane refueling stations (expected to be operational within 18-24 months) in more than a dozen U.S. metropolitan areas including Austin, Dallas, Houston), as well as support the purchase of dedicated propane school buses and vehicles. CleanFUEL USA (Georgetown, Texas) is also a partner in this project. Other goals for this project include: marketing campaigns to educate various municipal/state and private fleet operators about the advantages of using LPG-fueled fleet vehicles.

- An $8.6 million Virginia Department of Mines, Minerals and Energy project, in cooperation with a national coalition led by Alliance AutoGas (of Ashville, N.C.), for the construction of 17 new propane fueling stations along roadways from Washington, D.C. to Mississippi and Florida.
- A Triangle J Council of Governments initiative, under a $12.3 million grant, will deploy eight propane stations, 363 propane vehicles, and other alternative fuel vehicles in North Carolina and South Carolina.
- A $10.1 million Central Indiana Clean Cities project will convert more than 600 light-duty trucks to run on a propane-gasoline bi-fuel system and deploy other alternative fuel vehicles/fuel stations.
- Nearly $9 million will be used to convert about 1000 Washington D.C. taxicabs to operate on a propane/gasoline bi-fuel system, and build several propane fueling stations.

7 Results and Summary

Synthetic LPG as a key byproduct, with gasoline as the major product, can be produced commercially from coal or natural gas using the ExxonMobil MTG process. Also, a second-generation MTG plant has started up in China during 2009. In these MTG processes, coal or NG is first converted to syngas (a mixture of H_2 plus CO) to produce methanol which is then converted to DME for subsequent production of gasoline and LPG. Similarly, DME, which is often described as "synthetic LPG", can be produced commercially from coal or natural gas. China has already built several coal-to-DME DME plants. Also, key technologies to produce bio-LPG or bio-DME from biomass (including black liquor from pulp/paper mils) gasification are currently under development. It is likely that a few of these technologies (e.g., the Haldor Topsoe TIGAS process or the Haldor Topsoe DME process) can be commercialized within the next three to five years.

Various groups have proposed novel concepts to produce synthetic LPG. Most of these would require significant additional funds and time before one could realistically evaluate their economic competitiveness to conventional LPG. Two important concepts (with key catalysts proven only in bench-scale units) for the synthesis of LPG are: (i) the Japan Gas Synthesis Ltd. (JGS) process to convert syngas directly to LPG, and (ii) the University of Kitakyushu (UK) process to convert DME to LPG. Initial studies show relatively high once-through conversions as well as high selectivity for LPG for (i) the JGS catalysts, and (ii) the UK catalysts.

A few of these novel processes (e.g., the concept proposed by the MSU for converting vegetable oil-based fractions via conventional catalytic cracking processes used widely in petroleum refining) require corn/soybean type vegetable oils as feedstock. However, due to the ongoing concerns on increase in food prices if such oils are used for the production of renewable fuels, these processes can only be economically attractive if large-scale low-cost algae-based oils can be produced in the future. The Isis Innovation process (from Oxford University, UK) for converting glycerol (a byproduct from bio-diesel production based on vegetable oils) does provide a pathway to produce bio-DME; however, the process also requires hydrogen, preferably made from renewable resources if the DME product would need to be sold as 100% Green-DME. In general, due to the ongoing debates on the use of vegetable oils (which are typically used as a food resource) for the production of renewable fuels, this process would be better accepted if processes for the production of algae-based non-food oils are commercialized.

Our economic studies indicate that for a biomass-gasification based DME plant or a LPG plant processing 3,000 tons/day of wood (assuming that the JGS process can be scaled up), would cost about \$650 million to \$675 million (July 2009 \$). For such a plant producing about 69.3 million gallons per year of equivalent propane, the Cost of Production (COP) at 13% ROI (Return on Investment) would be about \$2.43/gallon of propane-equivalent DME with dry wood price at \$40/ton and price of electricity at \$0.08/kwhr. If the price of wood were increased to \$70/ton, the COP would be \$2.83 gallon of propane. For a similar biomass-to-LPG plant, the COP would be about \$2.31/gallon of propane at a wood price of \$40/ton. These costs include partial recovery of CO_2 that would be emitted from such plants; however, the cost of CO_2 sequestration is not included. Based on historical price trends for propane (at about 50-80% of petroleum crude prices in \$/bbl), a COP of \$2.31/gallon would correspond to a crude price of \$150/bbl (with propane at 65% of crude).

For LPG production from coal in capital-intensive mega-scale MTG plants, processing about 23,200 tons/day of coal, the capital cost would be about \$4 billion (July 2009 \$) with the production of about 115 million gallons/year of propane and 607 million gallons of gasoline (plus 111 MW of electricity). The CAPEX includes CO_2 capture and sequestration. The RSP would be about \$0.85/gallon of propane (corresponds to a petroleum crude price of ~ \$55/bbl) if the (i) cost of coal is \$35/ton (ii) gasoline selling price at the plan gate is $70/bbl and (iii) price of electricity is $0.08/kwhr. Similarly, for a moderately large coal-to-DME plant, processing about 3,860 tons/day of coal with nearly 119 million gallons/year of equivalent propane product plus 173 MW of electricity, the capital cost would be nearly $1.0 billion and the RSP for DME would be $1.35/gallon of equivalent propane (or crude price of $87/bbl) if the cost of coal is $35/ton and electricity is sold at $0.08/kwhr. Thus, under the economic assumptions for these studies, such synthetic or bio-LPG/DME technologies would be quite competitive to conventional fossil-fuel based LPG if significant federal taxes are imposed in the future for GHG emissions from various fossil fuels.

Our key recommendations are:

- PERC should play a leadership role in educating the U.S. LPG industry about the commercial potentials of synthetic or bio-LPG/DME, especially in reducing GHG emissions through the co-processing of coal plus biomass, or natural gas plus biomass.
- PERC should evaluate the technology from DieselGas Technologies Inc. (from Australia) for using 15-40% propane in existing diesel engines; if their claims are confirmed, the concept could also be extended to the use of LPG/DME blends.
- For early market penetration, PERC should fund suitable experimental projects (with participation of key stakeholders such as specific oil companies, other firms who are already active in promoting synthetic LPG or DME, and other organizations interested in promoting LPG-fueled vehicles including the Texas Railroad Commission, Alliance AutoGas Inc., or CleanFUEL USA) to determine the extent of safe DME addition levels in LPG/DME blend fuels (i) for home cooking and CHP markets, and (ii) as transportation fuels in key fleet applications.
- PERC should also consider funding, jointly with key industrial partners, experimental programs to:
    - Demonstrate if the VES Bioreforming technology can be modified to attain high yields for propane (vs. gasoline and diesel type liquids) from specific biomass resources.
    - Demonstrate suitable reactor systems for using the JGS catalysts (for the production of LPG from syngas) and the U of Kitakyushu catalysts (for the conversion of DME to LPG).
    - Evaluate if the GTI IH^2 process can be modified to provide relatively high yields of propane from biomass.
    - Evaluate site-specific economics for the production of (i) bio-DME from glycerol (the Isis Innovation process), and (ii) the CRI process to make methanol from CO_2 and H_2.
    - Further evaluate the GTI (i) POGT processes to produce DME from key biogas resources, and (ii) the IH^2 process to produce LPG as a byproduct with gasoline/diesel as byproducts.
    - Demonstrate safe levels of DME in LPG/DME blends for various industrial uses including home cooking, CHP, fuel cells, and transportation fuel applications.

8 References

1. http://www.epa.gov/OMS/renewablefuels/420f09023.htm
2. http://gov.ca.gov/press-release/4111/
3. Rockall, J., et al., "DME Opportunities in LP Gas Markets," 2nd International DME Conference, London, 17th May, 2006.
4. Pass, M., M. Pass Consulting Ltd., Canada, "Safety Assessment of DME Fuel,", Prepared for the Transportation Development Center, Safety and Security, Transport Canada, April 1997.
5. Otto, K., Purvin & Gertz Inc., "Global LP Gas Supply & Demand," 22nd World LP Gas Forum, Rio de Janeiro, Brazil, Oct. 8th, 2009.
6. Kelly, M., World LP Gas Association, "LP Gas the Efficient Alternative for Developing Countries," 7th Global Forum on Sustainable Energy, 21-23 November, 2007, Vienna, Austria.
7. http://www.reuters.com/article/rbssOilGasRefiningMarketing/idUSSEO11055620091021
8. ExxonMobil Research and Engineering, "ExxonMobil Methanol to Gasoline (MTG) Technology", Gasification Technology Conference, October 2009.
9. Haldor Topsoe A/S : www.topsoe.com
10. http://www.toyo-eng.co.jp/en/advantage/technology/energy/dme/index.html
11. http://apps1.eere.energy.gov/news/news_detail.cfm/news_id=15663
12. Hsu, D. D., "Bio-fuels Beyond Ethanol," National Renewable Energy Lab., Public Meeting, September 9, 2008.
13. http://www.volvo.com/group/global/en-gb/newsmedia/pressreleases/NewsItemPage.htm?ItemId=69233&sl=en-gb
14. Mikita, Y., Iwatani Corporation, Japan, "Dimethyl Ether (DME) and the trend of Bio DME production in China," Joint Task 40/ERIA Workshop, Trade of Liquid Biomass in the Region Part-2, October 29, 2009.
15. http://www.virent.com/
16. Personal Communication from Mr. Larry Osgood, President, Consulting Solutions LLC. Jan'10.
17. Zhang, Q. et al., Fuel Processing Technology, 85 (2004) 1139.
18. Asami, K. et al., "Semi-indirect Synthesis of LPG from Syngas: Conversion of DME into LPG", Catalysis Today, 106 (2005) 247-251.
19. Marker, T., et al, "Integrated Hydro-pyrolysis and Hydro-conversion Process for Production of Gasoline and Diesel from Biomass," ; http://www.aicheproceedings.org/2009/Fall/data/papers/Paper171241.pdf
20. Hydrocarbon Processing, "New Process Produces Methanol from Waste," April 2009, page 21.
21. http://thinkgeoenergy.com/archives/2738
22. White, M. G. and Hernandez, R., "Bio-propane from Syngas and Acyl-Glycerides," Report submitted by Mississippi State Univ. to PERC, received by GTI from Mr. G. Kerr, Director, PERC
23. Bibber, L. V., et al, Research and Development Solutions, LLC. "Technical and Economic Assessment of Small- Scale Fischer-Tropsch Liquids Facilities," DOE/NETL -2007/1253, February 2007.
24. Propane Canada Journal, July/August 2009, page-6.
25. http://www.dieselgas.com.au/home.htm
26. Bollon, F., Presentation by TOTAL Inc., "DME Characteristics & DME Standardization," WLPG Conference, September 2008.
27. Sloan, M. et al., ICF International Inc., "2009 Propane Market Outlook," Report Prepared for PERC, Report Provided to GTI by Mr. G. Kerr of PERC.
28. PERC data : www.propanecouncil.org
29. Lee, S. et al, "Performance and Emission Characteristics of an SI Engine Operated with DME Blended LPG Fuel," Fuel, 88 (2009), 1009-1015.

30. T A Semelsberger, T. A. et al, "Dimethyl Ether (DME) as an alternative fuel", Jnl of Power Sources, 156 (2006) 497-511.
31. Perlack, R. D. et al, "Biomass as Feedstock for a Bio-energy and Bio-products Industry: the Technical Feasibility of a Billion-Ton Annual Supply," DOE-GO-102995-2135.
32. http://www.ucsusa.org/global_warming/solutions/big_picture_solutions/climate-2030-blueprint.html
33. http://spectrum.andritz.com/archive/archive-online/iss_17/art_17_12.htm
34. http://www.choren.com/en/biomass_to_energy/carbo-v_technology/
35. http://www.congressional.energy.gov/documents/10-21-09_Final_Testimony_(Klara)_(NETL).pdf
36. Prof Ni Weidou, Tsinghua University, Chairman of the Steering Committee of Tsinghua-BP Clean Energy Research & Education Center, China; http://gcep.stanford.edu/pdfs/RxsY3908kaqwVPacX9DLcQ/niweidou_coal_mar05.pdf
37. http://jwinnie.biz/wordpress/?p=2015
38. Larson, E. D. et al., "A Cost-Benefit Analysis of Gasification-based Bio-refining in the Kraft Pulp and Paper Industry, Vol. 1., Princeton University, December 2006.
39. Kajitani, S., et al., "Direct-injection Diesel Engine Operated with Propane-DME Blend Fuel," SAE Document # 982536, October 1998.
40. Marchionna, M. et al., "Fundamental Investigations on Di-methyl Ether (DME) as LPG Substitute or Make-up for Domestic Uses," Fuel Processing Technology, 89 (2008) 1255-1261.
41. http://www.bluefuelenergy.com/
42. http://www.mitsuichem.com/csr/report/pdf/14_15_mk09en.pdf
43. Kruesi, P. R., Cato Research Corporation, personal communication (also, U.S. Patent # 7425315 B2)
44. Air Products and Chemicals, "Economic Analyses of LPMEOH Process,- As an Add-on to IGCC for Coproduction" Prepared for the U.S. DOE, Agreement # DE-FC22-92PC90543, October 1998.
45. Kreutz, T. G. et al, "Fischer Tropsch Fuels from Coal and Biomass," Princeton Environmental Institute, 21 August 2008.
46. Glasgow, B., Rocky Mountain Propane Association, Paper Presented at the 2008 Wyoming Winter Heating Conference.
47. McCollum, D. L. and Ogden, J. M., "Techno-economic Models for Carbon Dioxide Compression, Transportation and Storage and Correlations for Estimating CO_2 Density and Viscosity", 2006
48. Butane Propane News, October 2009.
49. G. K. Chitnis et al., "Production of Clean Gasoline from Coal: ExxonMobil's Methanol to Gasoline (MTG) Technology, "Petrotech-2009, January 11-15th, 2009, New Delhi, India.
50. Chemical Engineering, September 2009, Volume 116, Issue-9, page-12.

Appendix A. **Key Technologies and Process Concepts for the Production of Synthetic/Bio LPG and DME**

Near-term Technologies
These technologies have either been commercialized already (e.g., using natural gas or coal as feedstock) or would likely be commercialized within the next three to five years for biomass or biogas utilization.

1. *LPG as a byproduct from the ExxonMobil MTG process or the Haldor-Topsoe TIGAS (Topsoe Integrated Gasoline Synthesis) Process*

As shown in Figure A-1, there are multiple technical routes (e.g., direct coal liquefaction or indirect coal liquefaction) to primarily produce diesel or gasoline type liquid fuels from coal. In the schematic of the ExxonMobil MTG process, shown in Figure A-2, methanol produced from coal-derived synthesis gas is first converted to DME which is then converted to gasoline and LPG components. The ExxonMobil MTG process and the Haldor-Topsoe TIGAS technologies are referred to as the "indirect" liquefaction processes. In these processes coal is first gasified with steam/oxygen to produce synthesis gas for conversion to methanol (or methanol/DME in the TIGAS process), which is then converted to gasoline via a DME intermediate. These processes can also be used to utilize biomass (via gasification) or relatively low-cost natural gas.

As shown in Table A-1, typical yields (at about 17 wt% of total hydrocarbons if C_3/C_4 olefins are included) of LPG as a byproduct from the MTG process are significantly higher than those from other competing "direct" (e.g., H-Coal process) or FT-type (Fischer-Tropsch) "indirect" coal liquefaction technologies. Preliminary discussions with Haldor Topsoe A/S indicate that total LPG yields in the TIGAS process could be increased to about 25-30 wt% of the total hydrocarbons. Thus, depending on the future prices of petroleum crude and various government policies (e.g., the EPA/RFS proposal) with respect to energy independence and reductions in greenhouse gas emissions, future production of LPG (synthetic and bio-based) from such MTG/TIGAS type processes in the U.S. could be quite significant.

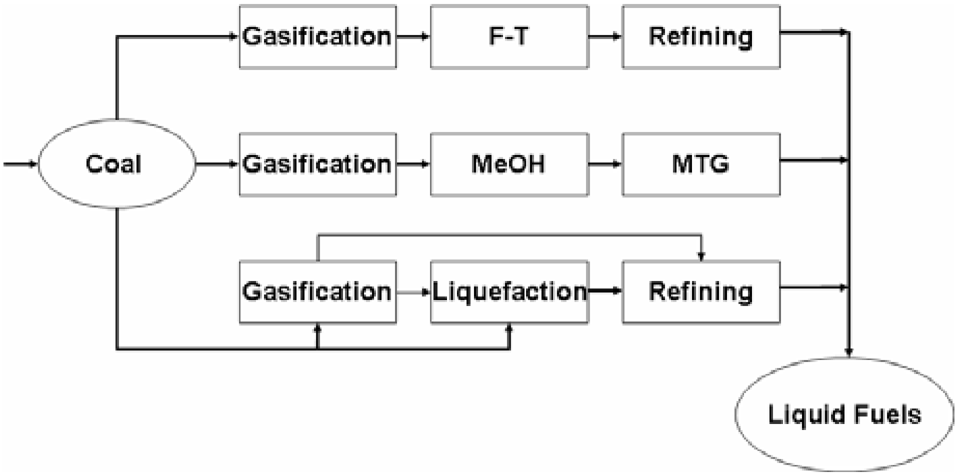


Figure A-1 Various Processes for Conversion of Coal to Liquid Fuels

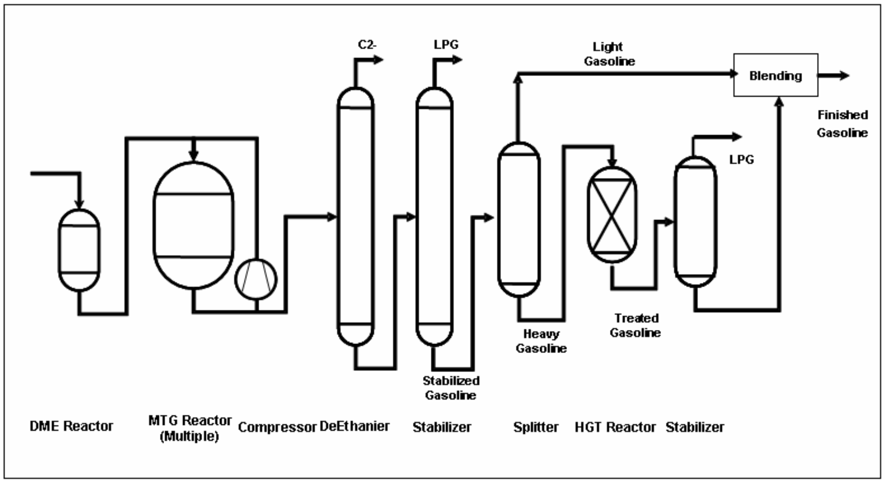


Figure A-2 Schematic of the ExxonMobil MTG Process[8]

The MTG process was commercialized (using natural gas as feedstock) for a 14,000 BPD plant in New Zealand during the late 1980s. Due to economic reasons, the plant was later modified for the production of methanol only. The first second-generation MTG plant is now under construction in China by Jincheng Anthracite Mining Group (JAMG). The MTG plant is part of a demonstration-scale complex, which also includes a coal gasification plant and a methanol plant. The initial phase of the plant (startup: 2009) is designed for a capacity of 100,000 tons/year of coal feed, but it is expected to expand to one million tons/year of coal feed for the second stage of the project. ExxonMobil has recently also announced the first U.S. Coal-to-Liquids (CTL) license based on the MTG technology. DKRW Advanced Fuels LLC, through its subsidiary Medicine Bow Fuel and Power LLC, has licensed ExxonMobil's MTG technology for its 15,000 BPD CTL plant (expected startup in 2011) in Medicine Bow, Wyoming.

Table A-1 MTG Gasoline and LPG Yields vs. FT and H-Coal Products, Wt% of Total Hydrocarbons

Ref. [49]

	Low-Temp FT Process	High-Temp FT Process	H-Coal Direct Liquefaction	ExxonMobil MTG Process
Methane	5	8	"No C_1-C_4 yields reported"	0.7
Ethane + Ethylene	1	7		0.4
Propylene	2	11		0.2
Propane	1	2		4.3
Butylenes	2	9		1.1
Butane	1	1		10.9
C_5-160 C fraction	19	36	36.5	82.3
Distillate	22	16	43.2	-
Heavy Oil/wax	46	5	20	-
Water-soluble Oxygenates	1	5	0.3	0.1
Total	100	100	100	100

2. *Production of DME from methanol, coal, biomass or natural gas*

DME is currently produced commercially from methanol (made primarily from natural gas; a few plants produce it from coal) via dehydration technologies; the licensors include: Lurgi, JGC/Mitsubishi, and TOYO Engineering (the TOYO process has already been used in four commercial DME plants operating currently in China).

Several technologies (such as the liquid-phase LPDME process developed by Air Products and Chemicals Inc. (APCI), the JFE liquid-phase process or the Haldor Topsoe fixed-bed process) have also been developed for direct synthesis of DME from syngas. A schematic of the LPDME reactor is shown in Figure A-3. Eastman Chemical Company has commercialized the LPMEOH process, developed also by APCI, for the production of methanol from coal at their Kingsport, Tennessee, facility.

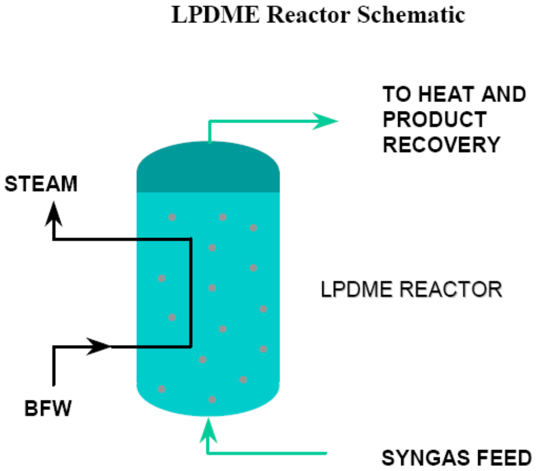


Figure A-3 The Air Products & Chemicals Liquid-phase Reactor Concept for Syngas to DME

For the indirect processes, the key chemistries are:

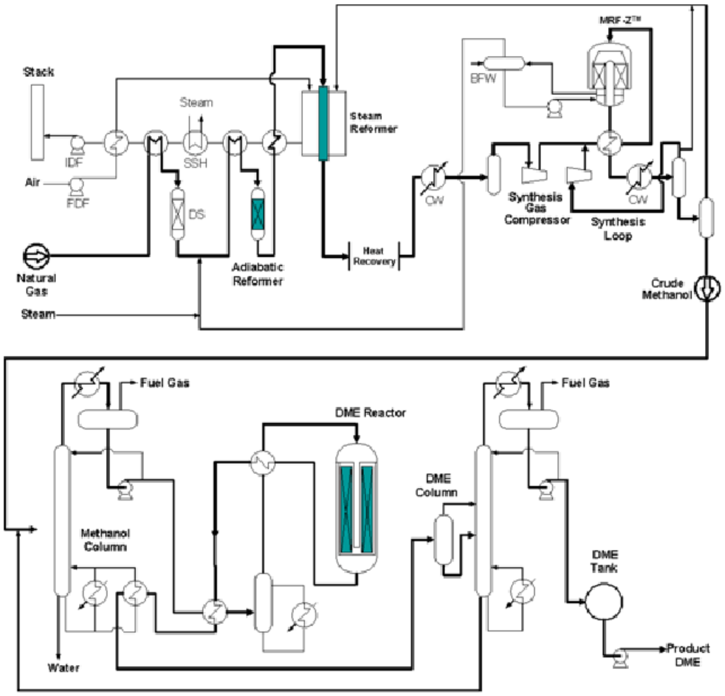
(1) methanol synthesis $CO + 2H_2 = CH_3OH$ (91 kJ/mol)

(2) methanol synthesis $CO_2 + 3H_2 = CH_3OH + H_2O$ (49 kJ/mol)

(3) methanol dehydration $2CH_3OH = CH_3OCH_3 + H_2O$ (23 kJ/mol)

3. *Production of DME from Coal or Natural Gas: Toyo Engineering (Japan) Process.*[10]

A conceptual diagram of this Toyo process for the production of DME is shown in Figure A-4. This is a two step process: (1) production of methanol from syngas, and (2) conversion of methanol to DME.



DME process flow

Figure A-4 Toyo Engineering Process for DME from Coal or Natural Gas
Ref. [10]

A Few Other Novel Process Concepts that Require Significant Additional R&D and Demonstration Efforts

1. *The process, developed jointly by the University of Kitakyushu , and the Japan Gas Synthesis Co. Ltd. (KKU-JGS), for direct synthesis of LPG from syngas.*[17]

The motivation for developing this process is that the KKU-JGS catalysts (for the conversion of synthesis gas – H_2 and CO, which can be produced from NG, biomass and coal) combine several operations into a single reactor. While there are various existing technologies for synthesis of (i) methanol and DME from syngas, (ii) DME from methanol, (iii) olefins from methanol and/or DME and (iv) LPG components via hydrogenation of olefins, the JGS catalyst combines all of these steps into a single reactor. This may lead to a cost-effective technology for the production of LPG from non-petroleum resources such as biomass, coal, petroleum coke and NG.

The KKU-JGS catalysts have been demonstrated in a 1 kg/day bench-scale unit. Based on literature data, they have developed two types of catalysts. Typical performance data are shown in Table A-2.

Specific Zn-Cr catalysts, with a beta-zeolite component: these catalysts have been shown to be quite stable at high temperatures and high pressures; however, the overall LPG productivity is relatively low.

Specific Cu-Zn catalysts, with a beta-zeolite component: these exhibit high LPG productivity; however, these are relatively less stable at high temperature and high pressure reaction conditions.

Table A-2 Comparative Data for KKU-JGS Catalyst Performance

Catalyst	Cu-Zn	Zn-Cr
Reaction Pressure, MPa	2.1	2.1
Temp., °C	375	375
CO conversion, %	76.3	72.0
Product Yield, Carbon %		
Hydrocarbons (HC)	44.7	46.8
CO_2	31.5	25.1
DME	0.12	0.11
LPG content in HC, C %	84.5	78.0

- A key observation is that, for this KKU-JGS technology, reactor operating pressures (of ~300-700 psig) would be somewhat lower than that needed (~about 1,000-1,400 psig) for the synthesis of DME (which can also be used as a LPG substitute for key applications: e.g., as a home cooking fuel).

A schematic of the proposed KKU-JGS process is shown in Figure-A-5.

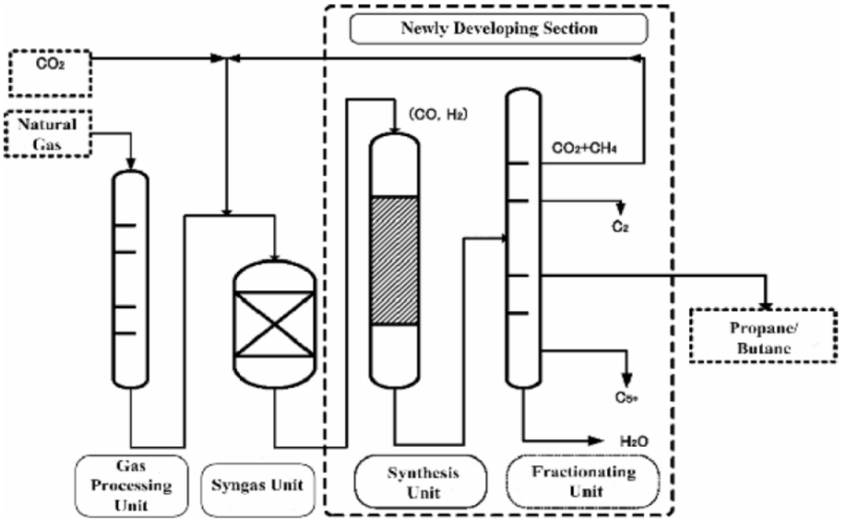


Figure A-5 Schematic Diagram of the KKU-JGS Natural Gas-to-LPG Process
Ref. [17]

Dr. H. Kaneko (hrkaneko@gas-gosei.co.jp) of the Japan Gas Synthesis Company is a key contact person to obtain other information on the status of their technology.

2. *Conversion of DME to LPG: Key Catalysts have been developed by the University of Kitakyushu, Japan.*[18]

Asami et al, from the University of Kitakyushu, have developed efficient hybrid catalysts consisting of zeolite and hydrogenation catalysts for the conversion of DME (plus hydrogen) to LPG. The once-through conversion of DME reached nearly 100% with selectivity for LPG of greater than 65% and with near-zero CO and CO_2 yields. Specific yield data based on hybrid catalyst are given in Table A-3.

Table A-3 Specific Yield Data from Hybrid Catalyst Performance

Conversion of DME, %	100.0
Product yield, (C %)	
Hydrocarbons	97.3
CO_2	0.0
CO	2.7
Hydrocarbon distribution, (C%)	
$C_1 + C_2$	15.4
C_3	25.6
C_4	39.5
C_5	12.8
C_6+	6.6
LPG (C_3+C_4)	65.2

Pressure: 2.1 MPa, Temperature: 375° C and H_2/DME = 3

3. *The BioForming Process Developed by VIRENT Energy Systems (VES) Inc.*[15]

VES has developed the BioForming process for the production of renewable liquid fuels from various biomass feedstocks. According to VES, plant sugars can be converted into various liquid fuels, *including LPG*, by their patented aqueous-phase reforming technology. According to Mr. Larry Osgood, president of Consulting Solutions LLC, this technology was initially developed to produce primarily propane from biomass. Later, based on initiatives from the U.S. DOE, VES had changed their focus to produce primarily gasoline and diesel. VES has formed a JV company with Shell Oil.

4. *The Integrated Hydropyrolysis and Hydroconversion (IH^2) Process, being developed by the Gas Technology Institute, for the Production of Gasoline/Diesel Fuel and LPG from Biomass*[19]

GTI is currently developing the IH^2 process for the conversion of biomass to gasoline and diesel fuels where LPG would be produced as byproduct (at about 10% volume of total liquid products). This process is carried out in two integrated stages, as shown in Figure A-6. The first stage is a medium pressure, catalytically-assisted, fast hydropyrolysis step completed in a fluid bed under moderate hydrogen pressure. Vapors from this stages pass directly to a second stage hydroconversion step where a hydrodeoxygenation catalyst removes all remaining oxygen and produces gasoline and diesel range liquids along with LPG as a byproduct. A unique feature of this process is that all the H_2 required in the process is produced by reforming the light hydrocarbons (mostly C_1 and C_2) produced in the process. Recently, this process has been selected by DOE for further development.

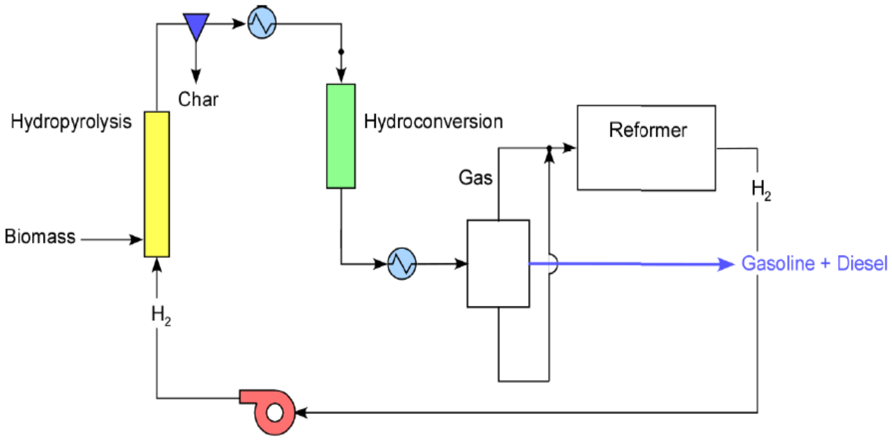


Figure A-6 GTI's IH^2 Process

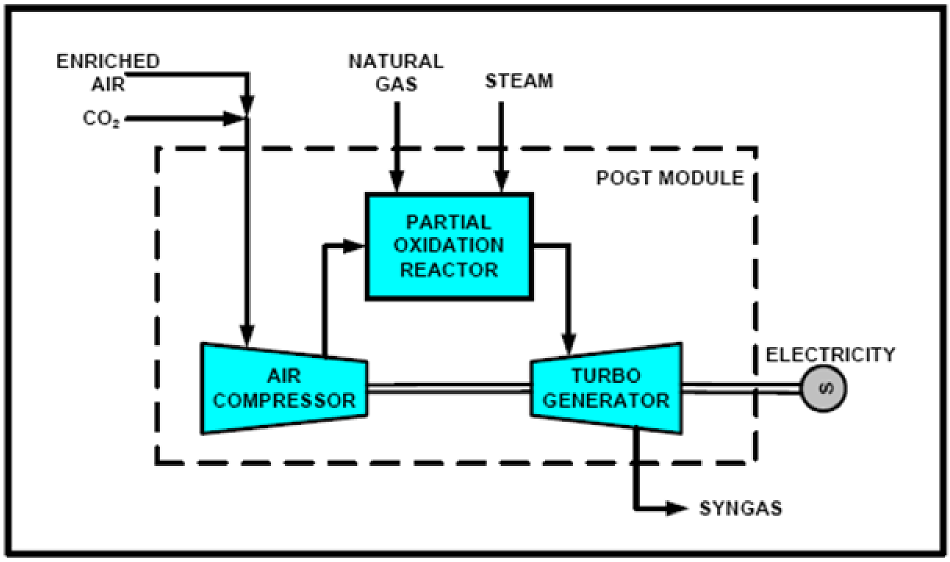
5. *Bio-propane from Acyl Glycerides (Mississippi State University: MSU)*

Prof. M. G. White and Prof. R. Hernandez of the MSU have proposed a process for the production of LPG via catalytic cracking of acyl glycerides (AG), the primary components of (i) microorganisms that can be grown using wastewater treatment infrastructure, (ii) vegetable oils (currently used for the production of biodiesel) and (iii) animal fats.[22] Catalytic cracking is a well-established technology in the petroleum industry. However, based on the published data from MSU, the primary products from catalytic cracking of the AG fractions are more suitable for the production of gasoline and diesel type fuels; the yields of the gaseous components (including LPG fractions) are relatively low (at only about 10-20 wt%).

With respect to the commercial production of bio-LPG, the MSU concept may be useful if the production of low-cost algae is commercialized in the future. Various groups are currently exploring the possibility of the use of algae to produce various liquid fuels. As an example, Royal Dutch Shell Plc. and HR Biopetroleum have built a pilot facility to grow marine algae, which would be harvested for producing vegetable oil for conversion to biofuels.[50] These two companies have formed a JV company, called Cellana, to further develop the project. The advantages of algae over other crops is their rapid growth – algae can double their mass several times a day and produce at least 15 times more oil per hectare than alternative crops, such as rape, palm, soya or Jatropha. Moreover, according to Shell Oil, algae cultivation facilities can be built on coastal land unsuitable for conventional agriculture.

6. *Partial-Oxidation based Gas Turbine (POGT) technology, for the coproduction of syngas plus electric power, being developed by GTI (Gas Technology Institute)*

GTI is currently developing a POGT concept (US Patent # 7,421,835 B2, September 9, 2008) for the co-production of syngas plus electric power from natural gas; the concept has been demonstrated at a scale of 250-kw using NG and air. A schematic of the proposed GTI process is shown in Figure-A-7. In this process, natural gas would be converted to syngas by reacting methane (in natural gas) with air under sub-stoichiometric combustion (referred to as partial oxidation) conditions. The syngas is then passed through the expander section of the gas turbine to generate power. The syngas effluent would then be cooled to generate steam (for additional power generation) and then utilized to produce LPG. Due to the relatively low footprint requirements for small-scale gas turbines, this concept could be especially attractive for the conversion of landfill gas or biogas to LPG.



¶

Figure A-7 GTI's Basic POGT Concept for the Production of Syngas from Natural Gas

7. The Haldor-Topsoe TIGAS (Topsoe Integrated Gasoline Synthesis) Process

In the TIGAS process, developed by Haldor Topsoe A/S of Denmark, syngas is converted to gasoline plus LPG.[9] This process is similar to the ExxonMobil MTG (Methanol-to-gasoline) process that was commercialized in New Zealand in the late 1980s; however, in the TIGAS process, the syngas is converted to liquids in one step using integrated reactors. A few important process differences are:

- In the TIGAS process, they typically use a hydrogen/CO ratio of ~ 1.0 to maximize per pass syngas conversion to DME :
    - $3 H_2 + 3 CO$ -→ CH_3OCH_3 (DME) + CO_2
    - The mixture of DME (and some DME) is then converted to gasoline range liquids (+ water) using zeolite catalysts.

In the MTG process, the typical H_2/CO ratio is ~2.0 as the reaction sequences are:

- Production of methanol from syngas: $2 H_2 + CO$ -→ CH_3OH
- Methanol Recovery and storage
- Methanol dehydration: $2 CH_3OH$ -→ $CH_3OCH_3 + H_2O$
- DME is then converted to gasoline + water

- Thus, in the TIGAS process, the reactors are closely integrated, and methanol is not separated as an initial product.

Typical data on product breakdown is given in Table A-4:

Table A-4 Typical Product Breakdown in the TIGAS Process

C_n	Total, wt%	Aromatics, wt%	Paraffins, wt%[**]
1	1		1
2	4		4
3	6		6[a]
4	13		13[a]
5	16		16
6	18	~0.1	18
7	14	1	13
8	13	6	7
9	8	7	1
10	7	7	0

** Naphthenes ~ 4 wt%; (a) Total LPG ~19 wt%

Ref. : J. Nerlov, Haldor Topsoe, "Gasification Based Synthesis of DME and Gasoline"

8. A Concept proposed by Cato Research Corporation of Golden, Colorado: (CRC)

Mr. Kruesi of CRC has proposed a two-step process for the production of propane from various raw materials including biomass, MSW (Municipality Solid Waste), coal and waste rubber (e.g., old automotive tires).[43] We have been specifically asked by PERC to review this proposed Cato Research process. The key steps are:

Step-1: Production of fine high-surface area carbon.

CRC has received a patent (U.S. Patent # 7425315 B2, September 16th, 2008) that teaches specific methods for extracting energy from organic materials through the production of very fine carbon powder plus water by contacting the organic material with a CO_2-rich or CO-rich gas. The basic exothermic reaction, usually favored at an operating temperature of about 350-500°C and at atmospheric pressure, is:

$$2\,(\text{-}CH_2\text{-}) + CO_2 \rightarrow 3\,C + 2\,H_2O$$

Where, $(\text{-}CH_2\text{-})$ represents various organic materials such as coal, biomass, and MSW.

This process for the production of "activated" high surface-area carbon (or Cato carbon) has been demonstrated using a small rotary-kiln at the Colorado School of Mines (under Professor Patrick Taylor).

Step-2: Production of Propane from the "Cato carbon" using a proprietary electrolytic technology.

According to Mr. Kruesi, this "Cato" carbon can be converted to propane using proprietary electrolytic technology that would use specific cathode catalysts. However, this step has not yet been demonstrated experimentally. We believe that the proof-of-concept demonstration completed already for the Step-1 CATO Research process is quite significant, and if relatively high yields for "Cato carbon" are proven at larger scales for various feedstock, this could potentially offer a method for the production of such fine carbon powders from several carbon-rich raw materials plus CO_2 from future CCS (Carbon Capture and Sequestration) projects. However, at this point, we cannot make any technical or economic analysis of the Step-2 concept since it has not been demonstrated experimentally.

Depending on the funding needs and licensing arrangements being offered by CRC, PERC may possibly consider exploring the possibility of conducting some small-scale laboratory experiments to verify the key concept of the so-called "electrolytic" method for converting the "Cato carbon" to propane.

9. The Isis Innovation Process for the production of methanol (and DME) from Glycerol.

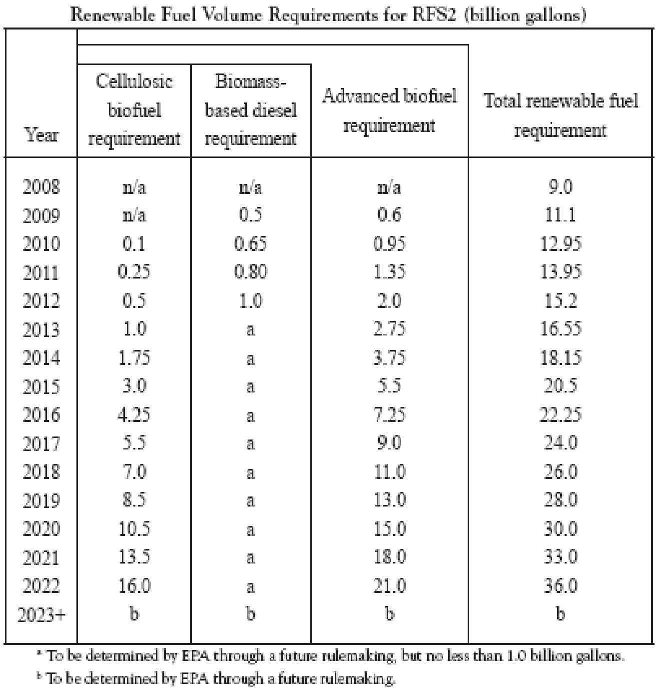
A new process being developed by Isis Innovation, the technology transfer company for the University of Oxford, UK, for the production of methanol from glycerol, a byproduct from biodiesel production.[20] The methanol can then be used in the production of Dimethyl Ether – DME - through methanol dehydration. DME can then be used as a LPG supplement for specific applications. Isis Innovation has recently announced that researchers in the University of Oxford chemistry department have discovered a new way to produce methanol (and thereby, DME from methanol) from glycerol which is a major byproduct in biodiesel production from various vegetable oils, such as corn oil and rapeseed oil. Although glycerol has applications in foods and personal care industries, it has no current large-scale industrial demand. About 90% of methanol is produced currently from natural gas. This Isis Innovation concept, if proven at a large-scale pilot plant, offers an alternative for the production of DME from various biomass resources including algae.

The Isis Innovation process involves catalytic hydrogenolysis of glycerol to methanol at about 100°C and 300-psig hydrogen. The key problems for this process concept for the production of bio-DME are the availability of low-cost vegetable oils and hydrogen. In the future, if low-cost algae derived oils can be produced in large quantities, a part of that oil can be reformed to produce hydrogen that can then be used to convert glycerol obtained as a byproduct from the bio-diesel production step with algae oil.

10. *Production of Methanol (and thereby, DME) from low-cost hydrogen (e.g., via water electrolysis using hydropower or wind turbine) and waste* CO_2

Carbon Recycling International Inc. (CRC: an Icelandic/US company) is planning to produce methanol/DME from hydrogen and carbon dioxide in a project in Iceland.[21] The company has developed specific catalyst systems to convert low-cost hydrogen and CO_2 (e.g., recovered from a power plant) to methanol without the use of any syngas (a mixture of hydrogen + CO).

Appendix B. **Specific Literature Information**



Renewable Fuel Volume Requirements for RFS2 (billion gallons)

Year	Cellulosic biofuel requirement	Biomass-based diesel requirement	Advanced biofuel requirement	Total renewable fuel requirement
2008	n/a	n/a	n/a	9.0
2009	n/a	0.5	0.6	11.1
2010	0.1	0.65	0.95	12.95
2011	0.25	0.80	1.35	13.95
2012	0.5	1.0	2.0	15.2
2013	1.0	a	2.75	16.55
2014	1.75	a	3.75	18.15
2015	3.0	a	5.5	20.5
2016	4.25	a	7.25	22.25
2017	5.5	a	9.0	24.0
2018	7.0	a	11.0	26.0
2019	8.5	a	13.0	28.0
2020	10.5	a	15.0	30.0
2021	13.5	a	18.0	33.0
2022	16.0	a	21.0	36.0
2023+	b	b	b	b

[a] To be determined by EPA through a future rulemaking, but no less than 1.0 billion gallons.

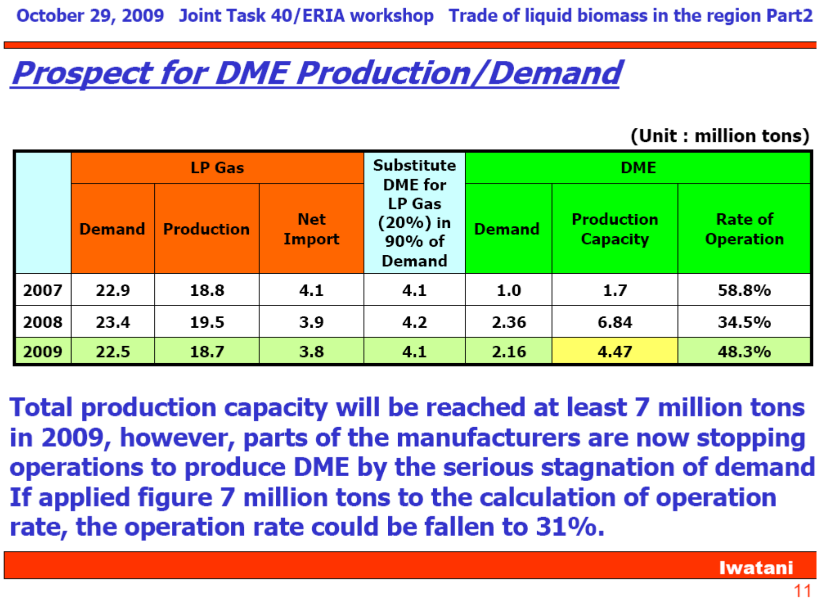
[b] To be determined by EPA through a future rulemaking.

Table B-1 EPA Proposal on National Renewable Fuel Standards (RFS)
Ref. [1]

Table B-2 EPA Proposal on GHG Thresholds for Various Bio-fuels under the RFS
Ref. [1]

Renewable Fuel (1)	20%
Advanced bio-fuel	50% (2)
Biomass-based diesel	50%
Cellulosic bio-fuel	60%

(1) The 20% criterion applies to plants that commenced construction after December 19th, 2007
(2) EPA is proposing to exercise the option to change this to 40%



October 29, 2009 Joint Task 40/ERIA workshop Trade of liquid biomass in the region Part2

Prospect for DME Production/Demand

(Unit : million tons)

	LP Gas			Substitute DME for LP Gas (20%) in 90% of Demand	DME		
	Demand	Production	Net Import		Demand	Production Capacity	Rate of Operation
2007	22.9	18.8	4.1	4.1	1.0	1.7	58.8%
2008	23.4	19.5	3.9	4.2	2.36	6.84	34.5%
2009	22.5	18.7	3.8	4.1	2.16	4.47	48.3%

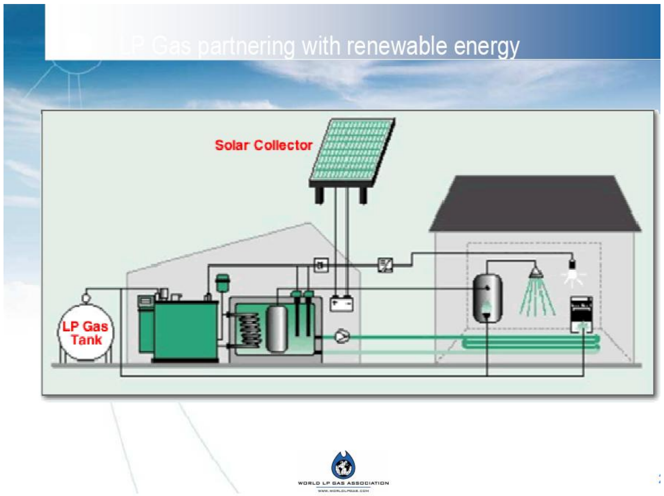
Total production capacity will be reached at least 7 million tons in 2009, however, parts of the manufacturers are now stopping operations to produce DME by the serious stagnation of demand If applied figure 7 million tons to the calculation of operation rate, the operation rate could be fallen to 31%.

Iwatani

11

Table B-3 Estimates on Current LPG & DME Demand and Production in China

Ref. [14]



LP Gas partnering with renewable energy

Figure B-1 A Concept, Being Promoted by the World LP Association, for LPG Fuel Partnering with Renewable Energy

Ref. [6]

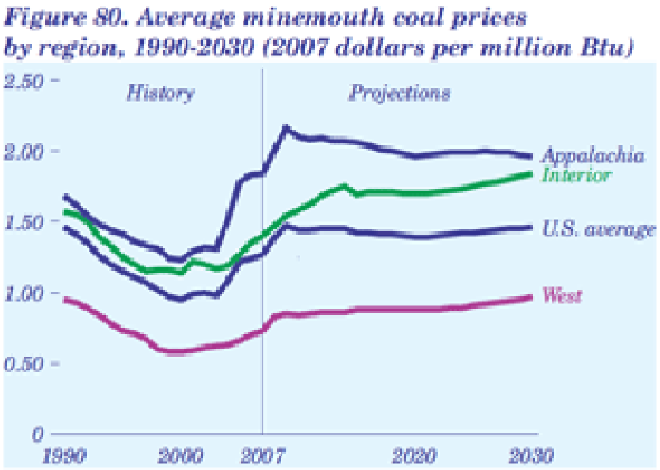


Figure B-2 EIA Projections on the Prices of Coal during 2015-2030

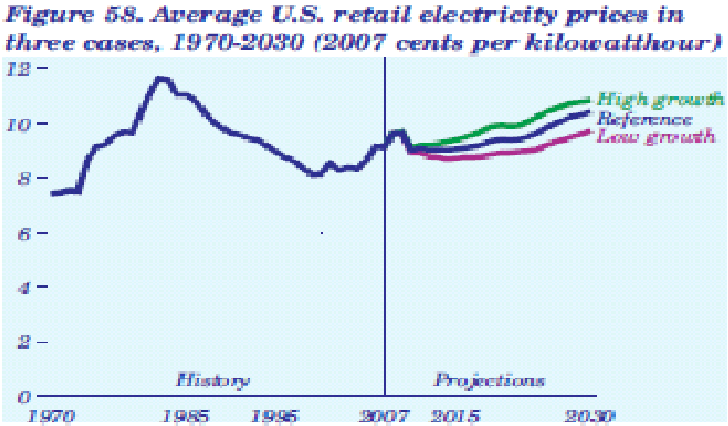


Figure B-3 EIA Projections on the Prices of Electricity during 2015-2030

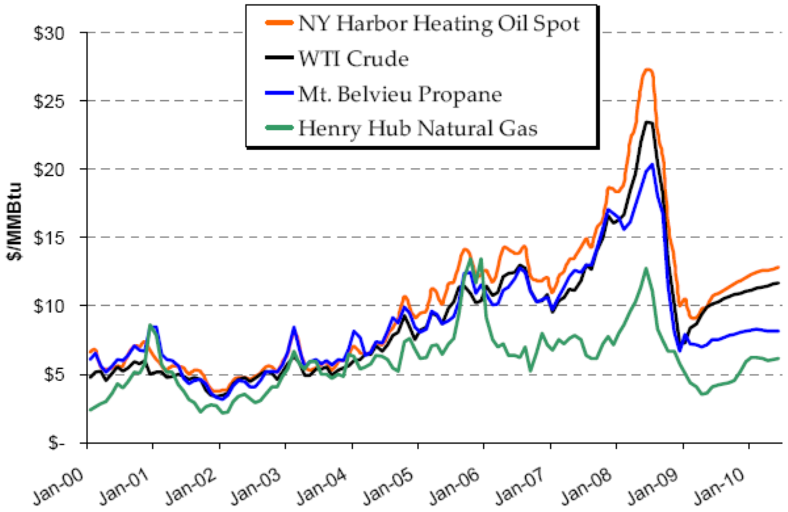
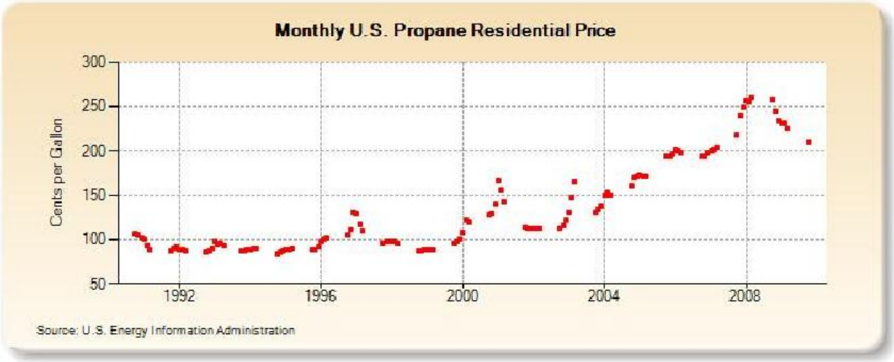


Figure B-4 Crude Price Trend during 1993-2008 ($/bbl)
Ref. [27]



U.S. Propane Residential Price (Cents per Gallon)

Figure B-5 Historical U.S. Propane Residential Prices

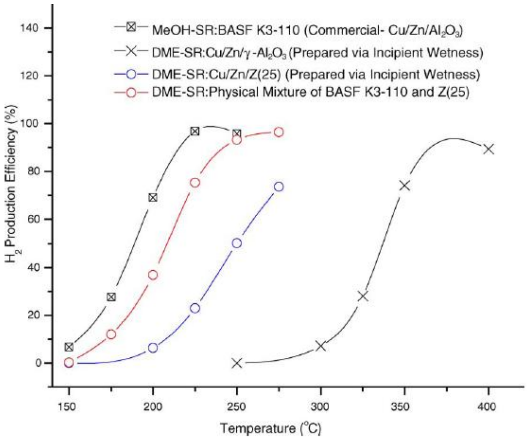


Fig. 10. Comparison of methanol steam reforming to dimethyl ether steam reforming over various catalsyts. Data reproduced from references [48,49].

Figure B-6 Literature Data on Reforming of DME and Methanol
Ref. [30]

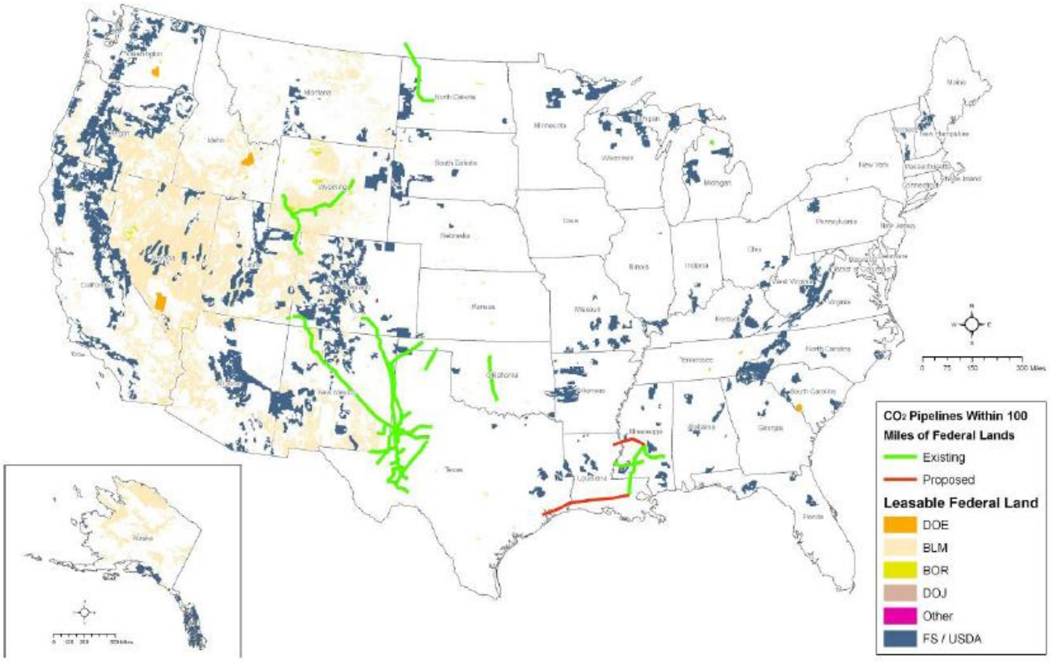
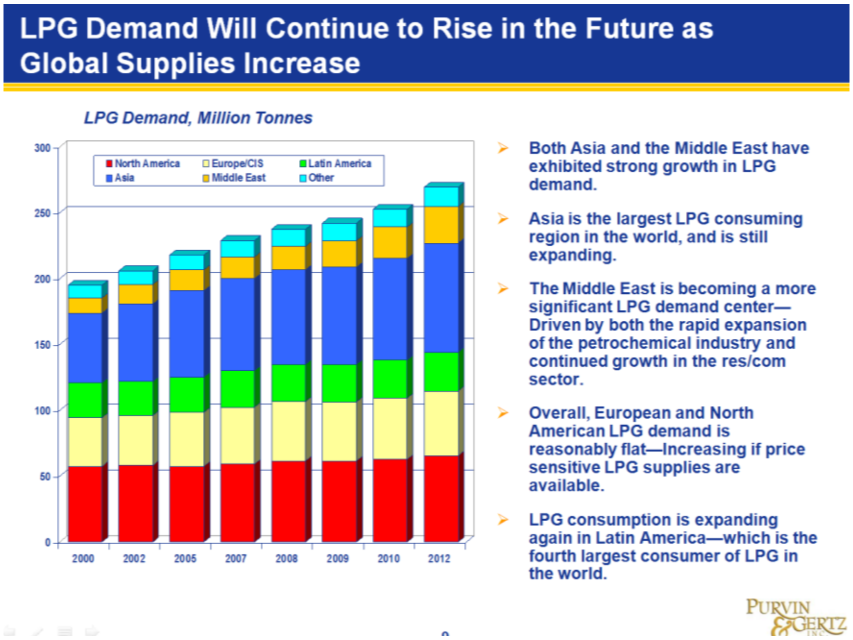


Figure B-7 Existing pipelines for transporting CO_2
Ref. [47]



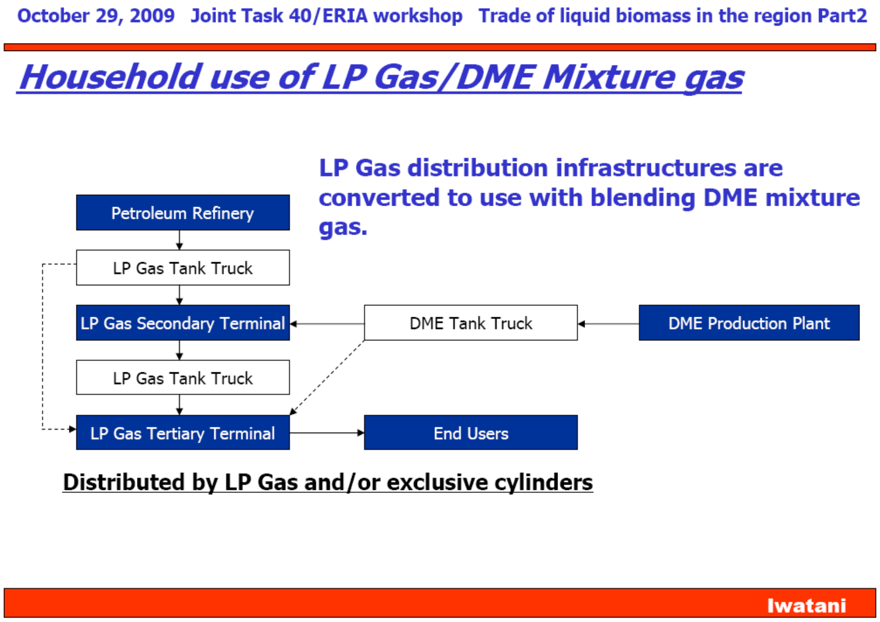
LPG Demand Will Continue to Rise in the Future as Global Supplies Increase

LPG Demand, Million Tonnes

- Both Asia and the Middle East have exhibited strong growth in LPG demand.
- Asia is the largest LPG consuming region in the world, and is still expanding.
- The Middle East is becoming a more significant LPG demand center—Driven by both the rapid expansion of the petrochemical industry and continued growth in the res/com sector.
- Overall, European and North American LPG demand is reasonably flat—Increasing if price sensitive LPG supplies are available.
- LPG consumption is expanding again in Latin America—which is the fourth largest consumer of LPG in the world.

PURVIN & GERTZ INC.

Figure B-8 Projections on Worldwide LPG Demand by 2012.
Ref. [5]



October 29, 2009 Joint Task 40/ERIA workshop Trade of liquid biomass in the region Part2

Household use of LP Gas/DME Mixture gas

LP Gas distribution infrastructures are converted to use with blending DME mixture gas.

Distributed by LP Gas and/or exclusive cylinders

Iwatani

Figure B-9 Household Use of LPG/DME Blends in China: Modification of LPG Distribution Infrastructures
Ref. [14]

Table C-1 Biomass and Coal Analysis (As-received)

Feed Resource	**Biomass**	**Pittsburgh #8 (a)**
Component, wt %		
Carbon	46.97	69.36
Hydrogen	5.85	5.18
Nitrogen	0.10	1.22
Chlorine	0.00	--
Sulfur	0.03	2.89
Oxygen	40.84	11.41
Ash	0.29	9.94
Moisture	5.92	--
Total	100.00	100.00
Higher Heating Value, Dry basis, Btu/lb	8,250	13,244 (b)

(a) Moisture : 6.0 wt%; (b) LHV/HHV ratio : 0.9685

Table C-2 Comparative Data for the Four Design Cases

Scoping Economic Case	**A**	**B**	**C**	**D**
Primary Products	Coproduction of DME plus Electricity using Biomass Gasification	Coproduce Propane plus Electricity using Biomass Gasification (Modification of Case A)	Mega-scale Plant Coproduce Gasoline, Propane and Electricity using Coal Gasification	Moderate Scale Plant Coproduce DME plus Electricity using Coal Gasification
Technology Gasification Liquid Production	GTI Air Products & Chemicals (APCI)	GTI Basic R&D: Japan Gas Synthesis Ltd.	Generic ExxonMobil MTG	GE APCI
Biomass Feed Rate (5.92 wt% moisture), metric tons/day	3,000	3,000	--	--
Coal Feed Rate (Bituminous, As Received), metric tons/day	--	--	23,200	3,859
DME Production, metric tons/day	630	--	--	1,079.8
Propane Production (DME Equivalent), metric tons/day	391.4	391.4	--	671.23
Propane Production, Bbl/day	5,024.1	5,024.1	8,305.8	8,620.5
Propane Production (DME Equivalent), Millions gallons/yr (90% plant capacity)	69.32	69.32	114.60	118.94
Gasoline Produced, Bbl/day	--	--	44,000	--
Net Sale of Electric Power, MW	26.3	26.3	111	172.8
CO_2 Capture	Yes	Yes	Yes	Yes
CO_2 Compression to 2,000 psig	No	No	Yes	Yes
Credit for CO_2	None	None	None	None

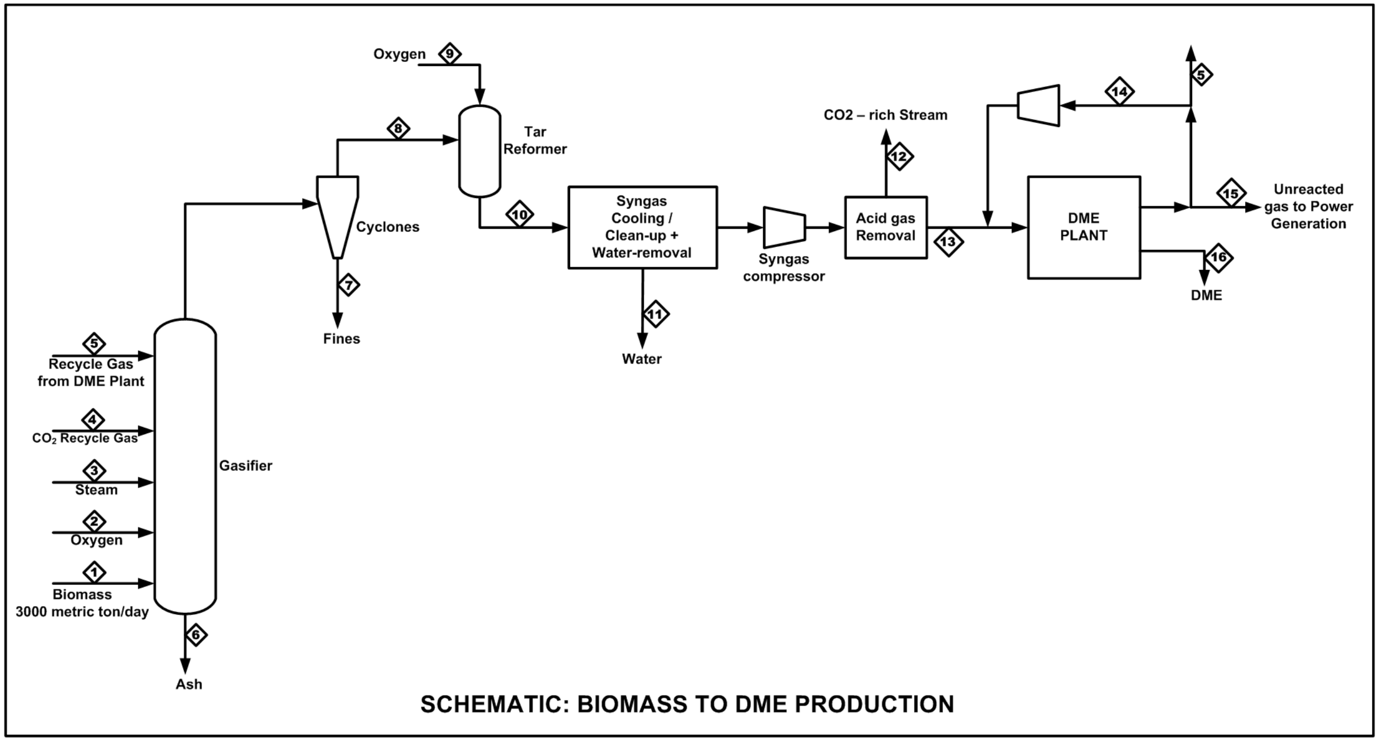


Figure C-1 Conceptual Process Flow Diagram: Biomass to DME (Design Case A; Key Mass Balances Given in Table C-1)

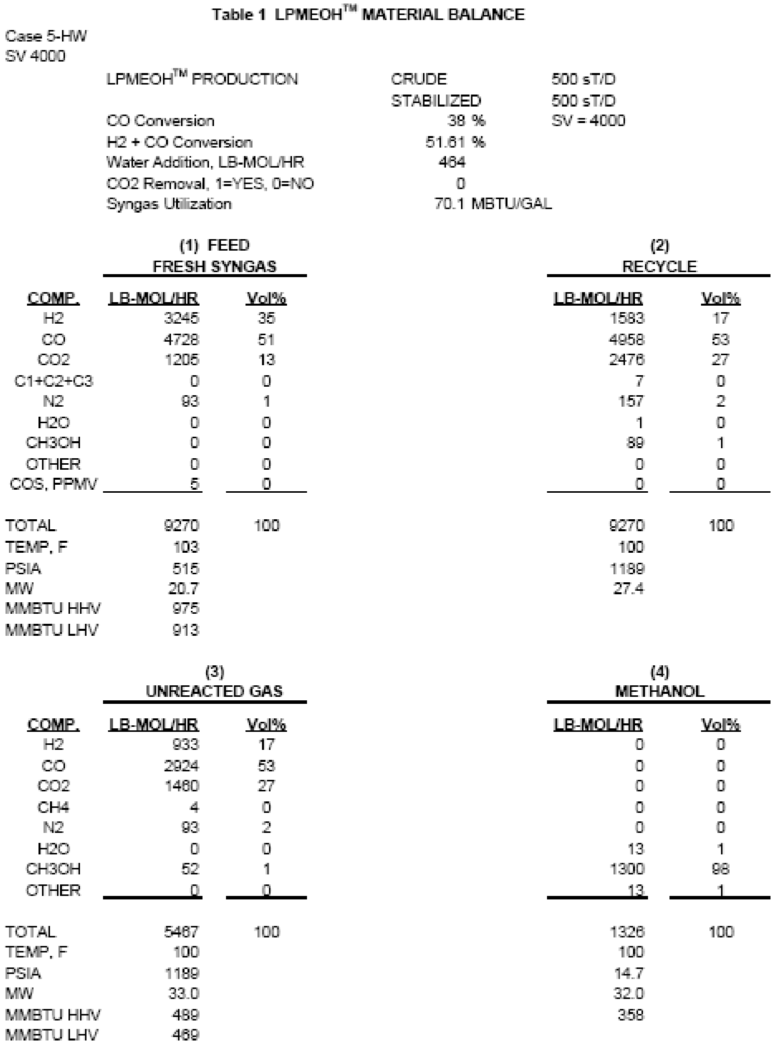


Table 1 LPMEOH^{TM} MATERIAL BALANCE

Case 5-HW
SV 4000

LPMEOH^{TM} PRODUCTION	CRUDE	500 sT/D
	STABILIZED	500 sT/D
CO Conversion	38 %	SV = 4000
H2 + CO Conversion	51.61 %	
Water Addition, LB-MOL/HR	464	
CO2 Removal, 1=YES, 0=NO	0	
Syngas Utilization	70.1 MBTU/GAL	

	(1) FEED FRESH SYNGAS		(2) RECYCLE	
COMP.	LB-MOL/HR	Vol%	LB-MOL/HR	Vol%
H2	3245	35	1583	17
CO	4728	51	4958	53
CO2	1205	13	2476	27
C1+C2+C3	0	0	7	0
N2	93	1	157	2
H2O	0	0	1	0
CH3OH	0	0	89	1
OTHER	0	0	0	0
COS, PPMV	5	0	0	0
TOTAL	9270	100	9270	100
TEMP, F	103		100	
PSIA	515		1189	
MW	20.7		27.4	
MMBTU HHV	975			
MMBTU LHV	913			

	(3) UNREACTED GAS		(4) METHANOL	
COMP.	LB-MOL/HR	Vol%	LB-MOL/HR	Vol%
H2	933	17	0	0
CO	2924	53	0	0
CO2	1460	27	0	0
CH4	4	0	0	0
N2	93	2	0	0
H2O	0	0	13	1
CH3OH	52	1	1300	98
OTHER	0	0	13	1
TOTAL	5467	100	1326	100
TEMP, F	100		100	
PSIA	1189		14.7	
MW	33.0		32.0	
MMBTU HHV	489		358	
MMBTU LHV	469			

Table C-3 Key Data Published by Air Products & Chemicals

Ref. [44]

Table C-4 Production of DME from Biomass: Flow Rates and T/P Conditions for Specific Streams (stream numbers are given in Figure C-1), Economic Case-A

Stream	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Description	Biomass Feed to Gasifier (moisture content, wt%: 5.92)	Oxygen to Gasifier	Steam to Gasifier	CO_2 Recycle Gas to Gasifier	Recycle Gas from DME Plant	Ash Discharge from Gasifier	Fines Recovered in Cyclones	Syngas Feed to Tar Reformer	Oxygen to Tar Reformer
Mol%									
CH_4					3.3				
C_2H_4									
C_2H_6									
C_3H_6									
C_3H_8									
C_4H_8									
C_4H_{10}									
CO					50.2				
CO_2					26.6				
H_2					18.0				
H_2O			100.00						
H_2S									
N_2		0.40			1.9				0.40
NH_3							0		
O_2		99.6			0		0		99.6
SO_2									
Total Flow, lb-mole/hr	--	--	--	--	5546.6	--	--	--	--
lb/hr	275,576	104,206	77,663	79,216	152,487	733	5,185	710,788	36,046
Temp., °F		306	450		392		60		306
Pressure, psia		200	335		517		500		

Table C-4 Continued

Stream	**10**	**11**	**12**	**13**	**14**	**16**
Description	Crude Syngas to Cooling/Clean-up & Water Removal	Water Removed In Gas Clean-up Section	CO_2 Rich Gas from the Acid Gas Removal Unit	Syngas Feed to DME Plant	Recycle gas to DME Reactor	DME Product
Composition, mol%						
CH_4	1.32		0.05	2.0	3.3	
C_2H_4	0.02		0.01			
C_2H_6	0.03		0.02			
C_3H_6	--					
C_3H_8	--					
C_4H_8	--					
C_4H_{10}	--					
CO	30.17		1.2	48.9	50.2	
CO_2	24.23		97.8	13.5	26.6	
H_2	21.00		0.9	35.0	18.0	
H_2O	22.77	100.0				
H_2S	0.01	trace				
N_2	0.38		0.02	0.6	1.9	
NH_3	0.07	trace				
O_2	--					
Total Flow, lb-mole/hr lb/hr	311,34.9-- 746,834	7089 127,610	7,634 331,521	179,60 374,096	179,60 488,368	1255.4 57,834
Temp., °F	1550					
Pressure, psia	165					

Table C-5 DME Production Plant Estimated Performance Summary (Economic Case A)

Production Figures	
DME Product Flow, metric tons/day	629.6
DME Thermal Output, MW (LHV)	206.8
DME Product, Propane (100% propane) Equivalent,	
Metric tons/day	391.373
Gallons/day	211,008.9
DME Lower Heating value, Kcal/kg	6,900
Propane Lower Heating Value, Kcal/kg	11,100
Net Power production for export, MW	26.3
Consumption Figures	
Wood Feed, metric tons/day (moisture level: 5.92 wt.%)	3,000
Wood Thermal Input, in MW (LHV) (LHV: 7,425 Btu/lb dry wood)	563.7
Oxygen to Gasifier, lb/hr	104,206
Oxygen to Tar Reformer, lb/hr	36,046
Total oxygen, lb/hr	140,252
Steam to Gasifier	77,663
Energy in Wood Input, MW (LHV)	563.7
Energy in DME plus Power Export, MW (LHV)[*]	255.5
Plant Net Thermal Efficiency (LHV), %	45.3

- Assume combined cycle power generation efficiency: 54%

Table C-6 Summary of Plant Electric Power Balance (MW)—Case A

Gasifier Island Auxiliaries	7.6	
Syngas Compressor	27.8	Compression from 125 psia to 1,285 psia
Compressor for CO_2 feed to Gasifier	2.3	
Compression of Recycle gas to DME Reactor	0.5	
Auxiliary Power for the DME Plant	1.2	
ASU	22.9	1,527 metric tons/day Oxygen
Rectisol (Refrigeration)	6.6	
Rectisol Auxiliaries	3.0	
Total power need	71.9	
Total Power produced from unconverted syngas **	93.9	Combined cycle: assume 54% efficiency (LHV)
Power Recovered from DME Recycle Gas Recycle to Gasifier	4.3	
Total Power Produced	98.2	
NET Excess Power	26.3	

** Assumes 99% recovery of CO/H_2/Methane lost with CO_2-rich gas

Table C-7 Summary of Capital Cost Estimate : Economic Case- A

Item	Total Field Cost TFC), Million $ (July 2009 $)	Comments
Gasifier Unit (including Drier, Gas Cooling plus Clean-up) + Tar Reformer [a]	175.0	Reference Cost Data is for GTI Biomass Gasifiers (Wood Feed: 564 MW, LHV Basis)
Syngas Compressor	16.1	
Compressor for CO_2 feed to Gasifier	2.3	
Air Separation Unit (ASU)	66.8	
Syngas Compressor		
Acid Gas Removal Unit	31.8	Rectisol AGR
DME Plant	62.3	
Expander for Recycle Gas to Gasifier	3.1	
Combined Cycle Power Plant	80.8	
Total Field Cost (ISBL)	438.2	
OSBL (assume 40% of ISBL, including land)	175.3	
Total Field Cost (TFC), ISBL + OSBL, 2009$	613.5	

a) Use Ref. x ($198.8 MM for a 815 MW, LHV basis, plant +15.5% Balance of Plant Cost) : 2007$
CE Plant Cost Index (CEPI): 2007=525.4468.2, July 2009= 512.1

Table C-8 Additional Capital Costs (MM$): Design Case A

Home Office, 8% of Total Field Cost (TFC)	49.1
License Fees, 3.5% of CAPEX for Gasifier plus DME & Rectisol Plants	9.4
Additional Capital Costs Subtotal, $MM	58.5
Total Field Cost, $MM	613.5
Total Capital Cost, $MM (July 2009 $)	672.0

Table C-9 Estimated Cost of Production for DME from Biomass Gasification (Capacity factor: 90%) : DME Production at 629.6 metric tons/day (July 2009 $)

Case	Base Case (Design A)	Sensitivity (Dry Wood at $70/ton)
DME Production, metric tons/day	629.6	629.6
Propane Production (DME Equivalent), metric tons/day: 100% Capacity	391.37	391.37
Propane Production (DME Equivalent), million gallons/yr: 100% Capacity	77.02	77.02
Total CAPEX, $MM (July 2009 $)	672	672
Annual capital related costs (Capital Charge at 13% of CAPEX : 25 years plant life & 13% ROI), $MM/yr	87.4	87.4
Labor + Utility, 5% of CAPEX, $MM/yr	33.6	33.6
Maintenance, Taxes + Insurance, 4% of CAPEX, $MM/yr	26.9	26.9
Cost of Wood (at $40/metric ton; dry basis), $MM/yr	37.1	64.9
Credit from Sale of Power (26.3 MW; 8 cents/kwhr), $MM/yr	(16.6)	(16.6)
Sub-total, total annual cost, $MM/yr	168.4	196.2
Total annual production, Million gallons/yr of Propane (DME Equivalent): 90% capacity factor	69.32	69.32
Production Cost of DME (propane equivalent), $/gallon	2.43	2.83

Appendix D. **Design Case-B -- Scoping Economics for LPG from Biomass using the Japan Gas Synthesis Concept**

Economic Case B

Total ISBL : $423 MM
OSBL : 40%
Total ISBL +OSBL : $592.2 MM

Home Office, 8% of Total Field Cost (TFC)	**47.4**
License Fees, 3.5% of CAPEX for Gasifier plus LPG & Rectisol Plants	9.0
Additional Capital Costs Subtotal, $MM	56.4
Total Field Cost, $MM	592.2
Total Capital Cost, $MM (July 2009 $)	**648.6**

Scoping Economics for the Production of Propane from Biomass Gasification (with CO_2 Capture) (Design Case A Modified to Produce Propane instead of DME)

Case	**Base Case (Design A)**	**Design Case B**
DME Production, metric tons/day	629.6	----
Propane Production (DME Equivalent), metric tons/day: 100% Capacity	391.37	391.37
Propane Production (DME Equivalent), million gallons/yr: 100% Capacity	77.02	77.02
Total CAPEX, $MM (July 2009 $)	672	648.6
Annual capital related costs (Capital Charge at 13% of CAPEX : 25 years plant life & 13% ROI), $MM/yr		84.3
Labor + Utility, 5% of CAPEX, $MM/yr		32.4
Maintenance, Taxes + Insurance, 4% of CAPEX, $MM/yr		25.9
Cost of Wood (at $40/metric ton; dry basis), $MM/yr		37.1
Credit from Sale of Power (31.3 MW; 8 cents/kwhr), $MM/yr		(19.8)
Sub-total, total annual cost, $MM/yr		159.9
Total annual production, Million gallons/yr of **Propane**: 90% capacity factor		69.32
Cost of **propane** , $/gallon		2.31

Appendix E. **Case-C -- Scoping Economics for the Production of LPG as a Byproduct (plus Gasoline as a major product) from Coal using the ExxonMobil MTG Process**

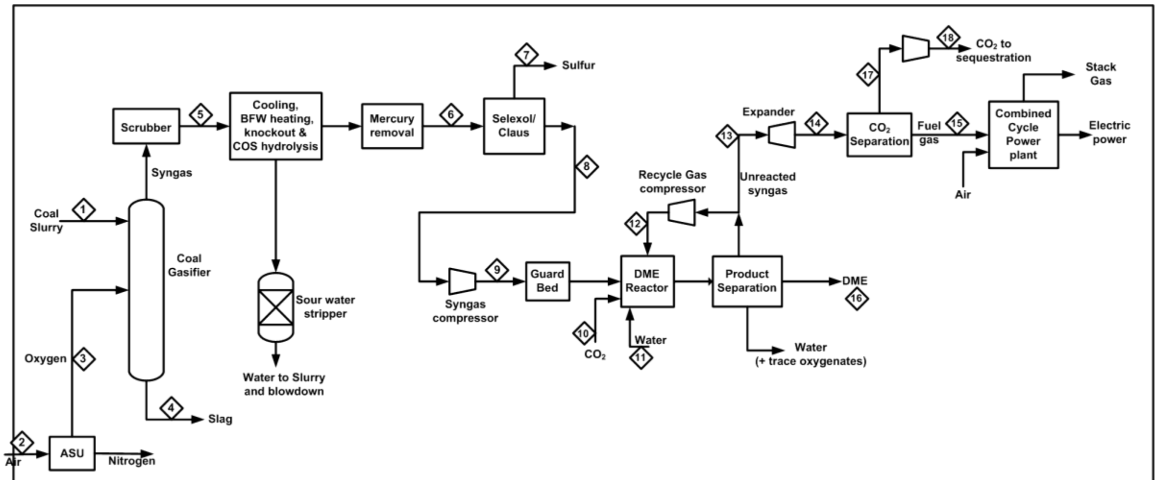
Appendix E: Design Case C
Scoping Economics for Mega-Scale Coal to Gasoline plus LPG Plant with CO_2 Capture
(Total Gasoline production: 50,000 BPD: 2009 NRC Study-----Year 2009 $)

	NRC Data	Modified for This Study (Capacity factor: 90%)
Coal rate, metric tons/day (as received)	23,200	23,200
Gasoline Produced, BPD	50,000	
Electric Power for Sale, MWe	111	111
Thermal Eff. (LHV), %	52.9	52.9
Total CAPEX, $MM (2009$)	4020	4020
Scoping Economics for Co-production of Gasoline plus LPG		*Assume : 12% of the total energy in gasoline is produced as Propane (100% Propane)*
Gasoline Produced, BPD		44,000
Propane, BPD Million gallons/year		8,305.8 127.3
Annual Capital Related Expenses, at 13% capital charge (25 years plant life + 13% ROI), $MM/yr		522.6
Annual Labor + Utility Costs, $MM/yr (5% of CAPEX)		201.0
Annual Maintenance, Taxes + Insurance costs, $MM/yr (4% of CAPEX)		160.8
Cost of Coal, $MM/yr ($40/ton)		304.8
Credit for sale of Electric Power (at 8 cents/kwhr)		(70.0)
Total annual costs, $MM/yr		1,119.2
Credit for Selling gasoline @ $60/bbl, annual credit, $MM/yr		(867.1)
Net annual Cost for Propane, $MM/yr		252.1
Production Cost of Propane, $/gal		1.98**

** *COP will be $0.85/gal if gasoline is sold at $70/bbl*

Appendix F. **Case-D -- Scoping Economics for the Production of DME (plus Electricity) from Coal**

Economic Design Case D



Process Block Flow Diagram: GE Gasifier-Based Co-production of DME and Electric Power from Coal

Table F-1 Coproduction of DME and Electric Power from Coal (Case D)

	1 Slurry	2 Air	3 Oxygen	4 Slag	5 Syngas	6 syngas	7 Sulfur	8 Syngas
V-L Mole-fraction								
Ar		0.0094	0.0320		0.0089	0.0096		0.0100
CH_4					0.0006	0.0007		0.0007
CO					0.4300	0.4604		0.4799
CO_2		0.0003			0.1314	0.1415		0.1115
COS					0.0003	0.0000		0.0000
H_2					0.3433	0.3688		0.3871
H_2O		0.0104			0.0673	0.0013		0.0009
H_2S					0.0083	0.0083		0
N_2		0.7722	0.0180		0.0088	0.0094		.0099
NH_3					0.0010	0.0002		0
O_2		0.2077	0.9500		0	0		0
Total					1.0	1.0		1.0
V-L Flow rate, (lbmol/hr)		45,785	10,010	0		33,329		31,379
V-L Flow rate (lb/hr)	166,893[a]	1,321,090	322,141	0		694,234	10,209	622,347
Dry Coal flow rate, (lb/hr)	333,218[b]			37,461				
Temp., F	60	60	207	300			355	112
Pressure, psia	1050	14.7	1,025	800			25	719

a) Includes slurry water and water from coal

b)Dry coal

Table F-1 Continued Coproduction of DME and Electric Power from Coal

	9 Compressed Syngas	10 CO_2 Feed to DME Reactor	11 Water Feed to DME Reactor	12 Syngas Recycle to DME Reactor	13 Unreacted Syngas to CO_2 Removal	14 Fuel Gas to Expander	15 Fuel Gas to Power Generation	CO_2 product
V-L Mole-fraction								
Ar		0.0	0.0	0.0162	0.0162	.0211		0.000
CH_4		0.0		0.0018	0.0018	.0023		0.000
CO		0.0		0.4799	0.4799	.6272		0.002
CO_2		1.0		0.2396	0.2396	.0063		0.997
COS		0.0		0	0			0.0000
H_2		0.0		0.2465	0.2465	0.3221		0.001
H_2O		0.0	1.0			0		0.00
H_2S		0.0				0		0
N_2		0.0	0.0	0.016	0.016	.0210		0.00
NH_3		0.0			0	0		0
O_2		0.0	0.0		0	0		0
Total			1.0	1.0	1.0	1.0		1.0
V-L Flow rate (lbmol/hr)	31,379	339.2	1449.6	31,379	19,405	14,848		4,571
V-L Flow rate (lb/hr)		14,928	26,115	0			10,209	
Solids flow rate, (lb/hr)								
Temp., F	250	60	60	88	60	60	355	112
Pressure, psia	1,310	1,265	1,265	1,310	1,130	1,130	25	719

a) Includes slurry water and water from coal

Table F-2 Coal-to-DME Plant Electric power Output including Auxiliary Load (Case 2)

	kW_e
Plant Output	
Total Combined Cycle Power Generation using fuel gas from Rectisol Unit	258,400
Auxiliary Load	
Coal handling/milling	1,710
Coal Slurry Pumps	400
Slag Handling & Dewatering	850
Air Separation Unit Main Air Compressor	45,121
Oxygen Compressor	8,790
Boiler Feed water Pumps	875
Cooling Tower Fans	290
Scrubber Pumps	203
Circulating water pumps	1,290
Selexol Plant Auxiliaries	1,976
Claus Plant Auxiliaries	162
DME Plant (Syngas compression plus Recycle Gas Compressor)	10,370
Expander Power Recovery (feed gas to Rectisol)	(4,200)
Rectisol AGR Unit (refrigeration)	6
Misc. Balance-of-plant	3,000
Transformer Losses	330
CO_2 Compression (to 2,000 psig)	14,410
Total Net Auxiliary Load, kW	85,583
Power for Sale, MW	172.82

Table F-3. Coal-to-DME Production Plant Estimated Performance Summary (Design Case D)

Production Figures	
DME Product Flow, metric tons/day DME Thermal Output, MW (LHV)	1079.8 354.7
DME Product, Propane (100% propane) Equivalent, Metric tons/day Gallons/day	671.23 362,060
DME Lower Heating value, Kcal/kg	6,900
Propane Lower Heating Value, Kcal/kg	11,100
Net Power production for sale, MW	172.82
Total Sulfur Production, tons/day	122.0
Total CO_2 to Sequestration, lb/hr[a]	200,779
Consumption Figures	
Coal Feed, lb/hr (moisture level: 6.00 wt. %)	354,488
Thermal Input, MW (LHV)	1,252.7
Oxygen (95 mol%) to Gasifier, lb/hr	322,141
Plant Overall Equivalent Efficiency	
Energy in Coal Input, MW (LHV)	1,252.7
Energy in DME plus Power Export, MW (LHV)[b]	674.8
Plant net Thermal Efficiency, Including CO_2 Compression to 2,000 psig, (LHV), %	53.9

a) CO_2 Purity : 99.9 mol%

b) Efficiency for Electric Power Generation (LHV) : 54%

Table F-4 Design Case D --- Capital Cost Data (2009 $)

Acct No.	Item/Description	Equipment	Material	Labor	Bare Erected Cost	Eng'g	Contingencies	Total Plant Cost, $MM
1	Coal & Sorbent Handling	8.619	1.656	7.421	17.696	1.416	4.778	23.89
2	Coal Slurry Prep. & Feed	13.307	2.703	10.929	26.939	2.155	7.274	36.37
3	Feed water and Misc. Systems	2.577	2.243	2.691	7.511	0.601	2.028	10.14
4.1/4.2	Gasifier/Syngas Cooling & Auxiliaries	70.835	31.129	58.204	160.167	12.813	43.245	216.23
4.3	Air Separation Unit/Oxidant Compression	67.859[a]			67.859	5.429	17.512 (18.322[b])	90.8 (91.610 [b])
4.4-4.9	Other Gasification Equipment	12.252	14.067	17.004	43.324	3.466	11.697	58.49
5A	Gas Cleanup	34.014	4.178	35.533	73.724	5.898	19.905	99.527 93.53[c]
9/10	Cooling Water + Ash/Sorbent Handling Systems							9.9 + 22.9 = 32.8
11/12	Accessory Electric Plant + Control Systems							19.3
13/14	Improvements to Site + Buildings							15.8
Syngas + DME Plant Recycle Gas Compressors (1.4 MW)								6.2
Fuel Gas Expander (Before Rectisol): 4.2 MW								1.8
CO_2 Removal (Rectisol)								51.0
DME Plant								91.0
Combined Cycle Power Plant								207.0
Total Plant Cost, $MM								954.4

a) Includes material + labor

b) Adjustment for slightly less Oxygen need (322,141 lb/hr vs. 327,454 lb/hr for the DOE Case)

c) Adjusted $6MM reduction due to the elimination of the Syngas Expander in the DOE Case

Table F-5 Total Capital Requirement (Case D)

	$MM, 2009 dollars
Total Plant Cost	954.4
Start-up	12.0
Owner's Cost	62.0
Total Capital Requirement	1028.4

Table F-6 Scoping Economics (Plant Capacity Factor: 90%), July 2009$

Case	Base Case (Design D)
DME Production, metric tons/day	1,079.8
Propane Production (DME Equivalent), metric tons/day: 100% Capacity	391.37
Propane Production, (DME Equivalent), gallons/day Millions gallons/yr (at 100% capacity)	362,060 132.152
Total CAPEX, $MM (July 2009 $)	1,028
Annual capital related costs (Capital Charge at 13% of CAPEX : 25 years plant life & 13% ROI), $MM/yr	133.6
Labor + Utility, 5% of CAPEX, $MM/yr	51.4
Maintenance, Taxes + Insurance, 4% of CAPEX, $MM/yr	41.1
Cost of Coal (at $35/metric ton: as received basis; 3,859.1 metric tons/day), $MM/yr	44.4
Credit for Sale of Sulfur (at $30/ton)	(1.2)
Credit from Sale of Power (172.82 MW; 8 cents/kwhr), $MM/yr	(109.0)
Credit for CO_2, $MM/yr	0
Sub-total, total annual cost, $MM/yr	160.3
Total annual production, Million gallons/yr of Propane (DME Equivalent): 90% capacity factor	118.937
The COP for Propane (DME equivalent), $/gallon	1.35*

* If electricity sale price were 6 cents/kwhr, the RSP for Propane would be $1.58/gallon.