A Life Cycle Comparison of Alternative Transportation Fuels

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ABSTRACT

The paper analyzes energy use and emissions per GJ of various fuels delivered to the vehicle fuel tank, covering extraction, fuel production, transportation, storage, and distribution phases of the life cycle of alternative fuels. Drawing on a number of existing studies, the modeling issues and approaches, main results and insights are summarized. The range of estimates in various studies is large; however, common patterns can be observed. The analysis indicates, that conventional gasoline fuel cycle has robust advantages with respect to energy efficiency, conventional pollutant emissions, and most importantly, existing infrastructure compared to alternative fuels. Fossil fuel based alternatives like CNG, NG-Methanol, NG-FTL do not result in significant improvement in fuel cycle environmental performance. Biofuels offer the benefits of lower and even negative GHG emissions, sustainability, and domestic fuel production. The herbaceous and woody biomass-based ethanol options are more attractive than producing ethanol and biodiesel from food products.

use of alternative transportation fuels. In addition, several state level initiatives call for alternatively fueled vehicles. The attention is likely to increase further as ways to comply with the Kyoto protocol on global climate change are investigated.

Alternatives to conventional gasoline and diesel fuels include: variants of conventional fuels such as reformulated gasoline (RFG) and reformulated or low sulfur diesel (RFD); natural gas based fuels such as compressed natural gas (CNG), liquefied natural gas (LNG) and Fischer-Tropsch liquids (FTL); electricity and biofuels. Biofuels include: ethanol from corn, ethanol or methanol from herbaceous biomass or woody biomass; and biodiesel from soybeans and rapeseed. The vehicles using these fuels can vary in terms of size (small, medium and heavy duty), fuel (dedicated single fuel or mixtures), vehicle technology (flexible fuel, fuel cell, hybrid), engine technology (spark ignition, direct injection), performance (range, fuel efficiency, acceleration), emission control technology (ULEV, Tier II) and fleet characteristics (age and mix).

INTRODUCTION

Unlike many other energy industries, transportation has not experienced significant fuel substitution, with petroleum based fuels accounting for over 95% of energy used. Recently, alternative transportation fuels have been receiving increasing attention as likely solutions to the problems of urban air quality, global warming and strategically important excessive dependence on imported oil. US Federal regulatory initiatives such as, the Clean Air Act Amendments of 1990, the Energy Policy Act of 1992 and the Alternative Motor Fuels Act of 1988 embody specific targets for the

Energy and environmental implications over the entire life cycle (covering fuel extraction, production, distribution, vehicle manufacture, use and disposal) have to be considered for an appropriate comparison of alternative fuel vehicles. Several recent studies have analyzed the life cycle energy and environmental performance of alternative fuels and vehicles. Studies such as those by the Argonne National Laboratory [18], Institute for Transportation Studies [4] 97], Ford Motors [8], Acurex Corporation [1], and Bell et al [2] compare a comprehensive set of alternative fuel vehicles (AFV), while many others carry out limited comparisons. For example, a 1998 report by the National Renewable

Energy Laboratory (NREL) compares life cycle performance of urban buses run on conventional diesel and biodiesel [12]. An earlier NREL study compares cars running on RFG and bio-ethanol [11]. Most of the studies compare and report environmental performance over the entire life cycle of AFVs including the vehicle use phase. However, the characteristics of the vehicles considered in the assessments vary across studies leading to difficulty in comparing results. We separate the vehicle use phase and focus on the fuel cycle environmental performance of alternative fuels. We focus on energy use and emissions per GJ of various fuels delivered to the vehicle fuel tank, covering extraction, fuel production, transportation, storage, and distribution phases of the life cycle of alternative fuels. We draw on the existing studies and summarize the modeling issues and approaches, main results and insights. We find that despite eliminating the vehicle performance related uncertainties, the range of values obtained from various studies is large, especially for biofuels.

DESCRIPTION OF FUEL CYCLES

PETROLEUM FUEL CYCLES

The fuel cycle for petroleum based fuels consists of four stages: crude petroleum extraction and recovery; crude oil transportation and storage; crude refining in a petroleum refinery to produce different individual fuels; and transportation, storage and distribution (TS&D) of fuels.

The United States imports more than half of its crude oil consumption. Conventional onshore production accounts for about 70% of US domestic crude output and about 77% of imported oil. About 20% of oil production is offshore. Enhanced extraction methods like thermal recovery through steam injection, chemical flooding and re-injection of gas (mainly CO₂, or poor quality associated gas) account for about 10% of US production. Only about 3% of foreign oil was produced using enhanced techniques.[18] Enhanced extraction technologies are more energy intensive.

As it emerges at the surface, the product of an oil well is a mixture of oil, water and gas, which must be separated in onsite treatment facilities. Emissions in crude extraction include products of fuel combustion (mainly diesel and natural gas) and non-process emissions associated with extraction and separation. In oil fields significant amount of natural gas is produced along with crude. If the quality or quantity of the associated natural gas is poor, it is either vented as methane, or flared as carbon dioxide, or re-injected for enhanced recovery. Almost one million MT of methane is vented annually in the US, most of it from oil wells. Oil extraction also results in substantial non-methane VOC emissions.

Crude oil is transported from oil fields to central storage terminals for blending and batching prior to large volume

transport. Small pipelines and trucks are used at this stage. Crude from these terminals is transported to oil refineries in ocean going tankers, long distance pipelines, trains, inland barges and tanker trucks. About 72% of US domestic and 23% of foreign crude oil was transported by pipelines. About 63% of foreign crude and 20% of domestic crude came by ocean tankers.[18] Residual oil used in ocean tankers and pipeline pumping/heating stations account for most of the energy consumption at this stage. Main sources of emissions are fuel combustion and non-process VOC emissions due to loading/unloading, leakage and spills.

Most of the petroleum refinery products consumed in US are produced domestically in about 160 refineries. The actual configuration, energy efficiency and emission performances of these refineries vary a lot depending on the size, output mix, input crude quality and local regulations. Petroleum refineries produce a wide range of products. Petroleum refining is a complex operation involving many unit processes and several joint/co products at each stage. The initial processes of crude oil distillation and catalytic naphtha cracking are common to all the products. Some energy intensive processes such as reforming, alkylation and isomerization are associated mainly with gasoline production, while thermal cracking (visbreaking), fluidized catalytic cracking and distillate hydrotreating are mainly associated with diesel production.

Reformulated gasoline requires production of low RVP, low sulfur, low aromatics gasoline which would be blended with oxygenates like MTBE, ETBE or Ethanol. To make RFG, refineries have to reduce the severity of reforming, increase the severity of catalytic cracking and increase alkylation, desulfurization and olefin extraction. MTBE and ETBE can either be produced within the refinery or produced at NGL plants. Production of RFG is expected to increase energy consumption and emissions at the refineries. Production of low sulfur gasoline and reformulated diesel (RFD) which have very low sulfur (5-50ppm) content would require more severe desulfurization combined with use of low sulfur feed stocks. Most of the sulfur occurs in the heavier fractions of crude oil. Fluid bed catalytic cracking (FCC) of these heavier fractions partially converts them to higher value lighter oils. Typically, diesel and gasoline components from FCC are the major contributors to sulfur in gasoline and diesel. Depending on whether only low sulfur gasoline or both low sulfur gasoline and diesel have to be produced, refineries can either desulfurize selected outputs of the FCC unit or FCC feed stock itself. Desulfurization is carried out by hydrotreating, i.e. reacting with hydrogen at higher temperature in the presence of catalysts, wherein the sulfur is converted into hydrogen sulfide gas. This is an energy intensive process. Hydrotreating gasoline results in loss of octane, which has to be compensated. Emissions in refineries include combustion emissions, non-combustion process emissions and fugitive emissions.

The refineries have a fair degree of flexibility in changing their product mix subject to limitations of installed processes, capacities, incoming crude quality etc. However, changes in product mix are rarely independent due to joint production from the same base input crude oil. An increase in the output of any one product would necessitate adjustments in the output and production processes of other products, and resultant changes in the total refinery energy use and emission performance. Ideally, an optimization model of the refinery should be used to estimate the marginal effects of changes in the output of a specific fuel, which is a complex, expensive exercise. Alternatively, aggregate refinery level energy use and emissions can be allocated to different products on the basis of relative energy content, refining energy intensity, relevant process areas, mass/volume, market value etc. Most of the existing studies use relative processing (refining) energy intensity as the basis for allocating aggregate refinery emissions to different refinery products. The final life cycle stage for petroleum based auto fuels includes transportation from refineries to bulk terminals (mostly by pipelines), storage at the bulk terminals, and distribution to refueling stations mostly by trucks. The main direct emission sources are fuel combustion at the pumping stations, tailpipe and other associated emissions with vehicular transportation, and leakage and spillage.

NATURAL GAS FUEL CYCLES

In 1996, motor vehicles accounted for a tiny 0.013% of a total of 22×10^{12} cubic feet of natural gas (NG) consumed in the US. Hence not much real data is available for modeling transportation systems largely based on natural gas. Data on specific sub components have to be estimated from literature or pilot plants and projected. Results can vary significantly depending on the initial assumptions and data sources used, especially since there are no aggregate data for overall model validation.

The natural gas based fuel cycle can be separated into four stages: extraction, processing, transportation and storage, and distribution. Raw natural gas is a mixture of methane, hydrocarbons, water, nitrogen, CO_2 , and sulfurous compounds. The quality varies considerably across locations and over time. NG is found both onshore and offshore either in gas-only fields or in association with petroleum. About a quarter of NG in the US is from oil fields. The collected raw natural gas is sent through small pipelines to NG processing plants, typically located near the fields. Poor quality gas is either vented or flared or re-injected to improve the yield of oil wells. NG processing involves separation of gas from liquids such as water, crude oil and condensate. The higher value hydrocarbons like ethane, butane and propane are condensed, collected, processed and sold separately. The energy used for running the various process units is mainly its own gas output. Emissions at this stage are

mainly from burning natural gas to meet the energy needs, and flaring/venting of poor quality gas.

During the transportation and storage stage, natural gas is moved from processing plants to local distribution companies mainly through pipelines. This segment includes large pipelines, compressor stations and metering facilities. Storage facilities include underground caverns, spent fields or above ground LNG facilities. The distribution stage for conventional gas consumers mainly consists of piping, depressurizing and metering activities. The main emissions during these stages are from the pumping related activities.

Modeling for NG based transportation would require modifications to the current system of NG processing and distribution. Assumptions regarding the system set up and process choice differ across studies. For LNG, the gas has to be liquefied and stored in cryogenic containers. Liquefaction can be done at a centralized plant near the NG processing plants. Bulk LNG containers can then be transported from plants to bulk terminals by rail, barges or trucks. Trucks are usually used for transportation of LNG to retail distribution centers. Alternatively, NG can be transported to bulk terminals via pipelines and liquefied there in smaller scale liquefaction plants. Similarly for CNG, compression can take place either at bulk terminals or at retail refueling stations or at home. The transportation modes, efficiencies and environmental impacts vary based on the scenario assumed.

The conversion of natural gas to methanol involves three major steps: gasification, methanol synthesis and distillation. In the gasification step, NG is reformed with steam to produce CO and hydrogen. Burning supplemental NG generates high-pressure steam and high temperatures required for steam reforming. The initial reforming produces 3:1 ratio of hydrogen and carbon, while the required H:C ratio for methanol synthesis is 2:1. One can either add carbon in the form of CO_2 if available, or burn the excess hydrogen. In methanol synthesis, syngas (mixture of CO and hydrogen) is passed over a catalyst to produce methanol. Methanol is then distilled to remove water and higher alcohols. The current methanol conversion efficiencies range from 50% to 60%. However, the technology of catalytic conversion is improving rapidly. Several commercial process alternatives such as Lurgi-combined reforming, partial oxidation, ICI synthesis etc. are available [18][4]. Methanol TS&D is similar to gasoline.

The Fischer-Tropsch process for converting syngas (mixture of CO and Hydrogen) into liquid transportation fuel was developed during World-War II in Germany. The FT process produces liquid fuels with no sulfur and virtually no aromatics, which can be processed into diesel or gasoline. FT fuels are completely compatible

with existing infrastructure for transportation and retail distribution. Several commercial FT plants are currently in operation, e.g. Shell plant in Malaysia and Sasol plant in South Africa. The NG-FT conversion process involves three stages, production of syn-gas (mixture of carbon monoxide and hydrogen) from natural gas by steam reforming, FT catalytic conversion to liquid hydrocarbons, and upgradation to required fuel. In the FT process, syngas is blown over a catalyst made from cobalt, nickel or iron, which transforms syngas into a mixture of hydrocarbons. The composition of the hydrocarbon mix from the FT process mainly depends on temperature. Running the reaction vessel at higher temperatures (330-350C) will primarily produce gasoline and olefins. Cooler temperatures (180-250C) produce middle distillates and waxes [6]. As a result, there are several variations on the FT technology [7]. FT plants can either be located next to NGL processing plants or be built integrally with them. FT diesel can be transported similar to conventional diesel. The conversion efficiency of FT diesel plant is estimated to be about 57% based on a Bechtel design [18] and 60-63% based on the Shell process [7][17].

BIOFUELS

Biofuels include ethanol and biodiesel. Ethanol can be produced from corn, sugarcane, herbaceous biomass, woody biomass and waste. Biodiesel can be produced either directly by micro algae or by transesterification of vegetable oils, mainly soybean and rapeseed oil. Advantages of bio fuels are: (1) they are produced from renewable sources and hence sustainable in the long run; (2) energy crops can be grown in a wide variety of regions reducing dependence on specific sources of fossil fuels; (3) bio-fuel use can potentially reduce net carbon dioxide emissions to the atmosphere and address the global warming problem. However the net economic and environmental benefits of biofuels depend on the efficiencies of the production and conversion processes. The fuel cycle for biofuels includes corn/oilseed/biomass farming, transportation of farm output to biofuel production plants, biofuel production and biofuel TS&D. In addition, fertilizer and pesticide production and transport are included as separate stages.

Technologies for corn farming and corn ethanol production using wet and dry milling processes are mature. Current US production of corn ethanol is about 1.5 billion gallons per year [Wang 98]. Ethanol production from corn yields distillers grains, solubles, gluten, corn oil etc. as coproducts. Wet milling plants mainly use coal and may generate own electricity in co-generation plants. Smaller dry milling plants tend to use more natural gas and purchased electricity.

The main source of bio-diesel in the US is likely to be soybean oil. Soybean farming and soy oil production technologies are well established. In 1996, US

production of soybeans was 2177 million bushels and soybean oil production was 15,235 million pounds [18]. Bio-diesel is obtained by transesterification of soybean oil, which involves reaction of tryglycerides in soy oil with alcohol in the presence of catalyst, in this case, sodium hydroxide [18]. Bio-diesel cycles yield more valuable soymeal and glycerine as coproducts.

The most promising sources of biomass are switchgrass (herbaceous) and hybrid poplars (woody biomass), although many other sources including corn stover, sugarcane, napiergrass and municipal and agricultural waste can be used. [18][13] Short rotation woody crops like hybrid poplars are highly productive under short rotations of 4-7 years and have low requirements for nutrients, water, herbicides and pesticides and intermediate management. Hybrid poplars yield about 5.4 dry MT/acre/year of biomass. These can be grown on land previously used for crops or for pastureland. Attempts to grow poplars on forestland have been less successful [3]. Switchgrass has been traditionally used as ground cover to prevent soil erosion. Switchgrass is attractive due to its adaptability to a wide range of environments, high yields, low fertilizer and chemical requirements and flexibility as a forage and energy crop. Annual harvesting can begin after 2-3 years and can continue for more than 10 years. Biomass yields from switchgrass range from 2-7MT/acre/year, though yields as high as 15 tons have been reported [5]. Cultivating energy crops will alter land use patterns and lead to additional carbon sequestration due to changes in standing biomass and soil organic carbon content. Delucchi estimates carbon sequestration rates of 97-225 kg/dry ton of biomass harvested[4].

Biomass contains three major components, cellulose, hemicellulose and lignin. The details of the conversion process for making ethanol from lignocellulosic biomass have been discussed in several papers [13][5][10]. The steps can be summarized as:

- Physical and/or chemical treatment to make cellulose amenable to hydrolytic attack, including delignification to free cellulose and hemicellulose.
- Enzyme production
- Enzymatic hydrolysis or acid hydrolysis and depolymerization to free sugars
- Fermentation to produce ethanol and distillation
- Residue and coproduct processing.

Coproduct of woody and herbaceous alcohol cycle is electricity. Based on near term technologies, 1.73 and 0.865 kWh of electricity is generated per gallon of ethanol produced from woody and herbaceous biomass respectively [20]. Since alcohol is soluble in water, use of pipelines for transportation and distribution can result in contamination. Transportation by trains and trucks is more energy intensive and expensive.

FUEL CYCLE MODELING

In its essence, fuel cycle analysis is a complex accounting model attempting to keep track of a large number of interdependent processes and associated environmental impacts. Significant interdependencies arise from the use of all other fuels including residual oil, coal and electricity as intermediate energy inputs in the fuel cycles. The production processes also result in a number of co-products to which costs, energy and environmental impacts have to be allocated. While the modeling details vary across the studies, the basic structure is very similar and involves the following features.

- For fossil fuels, the fuel cycle is divided into four stages: feed stock extraction, feedstock transportation and storage, fuel production, and fuel transportation, storage and distribution.
- For biofuels the biomass farming stage replaces the feed stock extraction phase. The major inputs to farming include fertilizers and agricultural chemicals in addition to energy.
- For each of these stages the energy requirement and fuel mix are estimated.
- Depending on the equipment in which the fuel is combusted (boilers, vehicles, ocean tankers, compressors etc), appropriate combustion emission factors are used to estimate fuel combustion related emissions.
- Non-combustion emissions such as process emissions, venting/flaring and fugitive emissions are estimated separately for each stage.
- For bio fuels, lifecycle energy use and emissions for fertilizers and other inputs are accounted for.
- The emissions associated with joint products are allocated to different products based on selected criteria. Relative processing energy intensity is most commonly used as the basis of allocation for fossil fuels. Bases for coproduct allocation in the case of biofuels is less obvious.
- These individual stage energy use and emissions are then aggregated to estimate full fuel cycle emissions.

Since there are interdependencies arising from use of various fuels as intermediate energy inputs in the fuel cycle, adjustments are made to account for these. In some cases it is an exogenous one time adjustment from secondary sources (e.g. [16][11]) and in some models they are calculated endogenously within the model. e.g.[5][18].

Obviously, fuel cycle analysis involves modeling a large number of fuels, processes, process options transportation modes, and emission control options. A larger number of process energy use and emission parameters have to be estimated or assumed. Subjective judgements have to be made about boundaries of analysis, co-product allocation, future scenarios, technology trends etc. As a result, the final estimates of energy use and emissions per GJ of fuel delivered to the vehicle vary significantly across different studies,

especially for less commonly used fuels like bio-fuels. Reconciliation of differences is difficult since all the intermediate parameter estimates, calculations and assumptions are seldom available in published reports. Table 1 summarizes the range of values obtained in some recent studies. While the range of absolute estimates is large in the various studies, similar patterns were observed in relative performances of alternative fuels and qualitative conclusions based on them. We summarize the insights and judgements from existing studies and our additional analyses below.

Availability

Experts disagree on the amount of petroleum that could be extracted at prices close to current levels of \$21/barrel. Similarly, there is no consensus on the amount of natural gas that can be economically extracted at current price levels of \$2/MCF. Approximately 120 billion gallons of ethanol or 75 billion gallons of biodiesel are required to replace nearly 100 billion gallons of gasoline that currently fuel the US light duty fleet. Based on current and near term yields of bio-fuels from biomass, and biomass yields per acre from Wooley [21] and Wang [20], we estimate the land requirements. These are shown in Table 2. If all the fossil energy in biofuel production cycle was replaced with biofuels produced using sustainable methods, production and combustion of these would result in no net emissions of carbon dioxide. We assume that all fossil fuel use in biofuel production can be substituted on a MJ basis with biofuels. We also estimate land requirements for sustainable production as shown in Table 2. Currently about 60 million acres of crop land is idled in the US and one study by US Department of Agriculture, estimates that about 100 million acres of farm land would be available for energy crop production [3]. Additional land can be brought under biomass production by partly converting 125 million acres of pastureland available. Since US imports more than half of its crude oil requirements, even relatively small reductions in demand due to the use of biofuels can increase US energy security and provide a back stop technology limit on oil price increases. Under near term conversion technology conditions the price of bioethanol is reported to be 1.5 - 2.5 times the current equivalent price of gasoline and is projected to become less than 1.2 times and even cheaper than gasoline by 2015 with aggressive research and development [21][15].

Energy efficiency

The estimates of the energy efficiency (output energy at vehicle fuel tank/total fuel cycle energy input) of the conventional gasoline fuel cycle range from 79%-88%; a majority of estimates are around 82%. The energy efficiency for conventional diesel cycle is lower with most estimates between 88-91%. However, this lower efficiency of the diesel cycle is mostly an artifact of the allocation of total refinery energy consumption on the

basis of refining energy intensity to various co-products of petroleum refining. Reformulated gasoline production consumes 3-5% more energy than conventional gasoline. The energy efficiency of CNG fuel cycles is roughly the same as conventional gasoline cycle with estimates evenly distributed between 79% and 85%. The NG-Methanol cycle efficiency is much lower with most estimates around 60%. The NG-FTD cycle efficiencies range from 52-58%. Efficiencies for the average corn-ethanol cycle range from 45% to 59%. The reported wet milling cycle efficiency is slightly higher than the dry milling process. The biodiesel fuel cycle efficiency is much higher (69%) than the corn-ethanol cycle, as the conversion of soybeans to soy oil and biodiesel is relatively much less energy intensive than corn to ethanol conversion. The energy efficiency of the woody biomass ethanol cycle is generally in the 47-53% range though one study reports efficiency as high as 68%. The herbaceous biomass ethanol cycle is less energy efficient compared to woody biomass. However, comparing fuel cycle total energy for the biofuels with that of the fossil fuels is misleading. For bioalcohols and biodiesel, large amounts of energy are required in the conversion processes. For the fossil fuels, nature has already converted the biomass to these fuels (e.g., petroleum is formed by the decay and incomplete oxidation of biomass and animal debris buried in sedimentary rocks during geologic times), therefore, far less energy is required throughout the fossil fuel cycles. Only 10% of the biomass fuel cycle energy is required for biomass farming and transportation to an ethanol conversion facility, the remaining 90% is used in the conversion of biomass to ethanol and its transport, storage, and distribution. Further, most of the energy used in biomass conversion is renewable. A more relevant fuel cycle energy use comparison is to compare non-renewable fossil fuel energy use, since, particularly for the biomass ethanol, the majority of the energy used in the biomass conversion plant is from the biomass itself. Lowest efficiencies are observed for the electricity fuel cycle (23-29%). However, these are not directly comparable since these include conversion losses in electricity generation, and electric vehicles are much more efficient than internal combustion vehicles.

Global warming effects

Relative to conventional gasoline, the fuel cycle emissions from conventional diesel and CNG are 15-20% lower. Even though the energy efficiency of the CNG cycle is roughly equal to that of gasoline, use of natural gas in its life cycle stages results in lower carbon dioxide emissions. Natural gas to methanol and FTD fuel cycles have significantly higher (150% – 300%) carbon dioxide emissions than gasoline cycle. Reformulated gasoline results in slightly higher CO₂ emissions. The low sulfur diesel fuel cycle will have roughly the same carbon dioxide emissions as conventional gasoline due to increased energy intensity of desulfurization. Corn based ethanol and biodiesel fuel

cycles result in significantly higher carbon dioxide emissions (200-250%) due to relatively high fertilizer, pesticide use in cultivation and fossil energy intensity. Only natural gas to FTD and electricity fuel cycles result in higher carbon dioxide emissions than corn ethanol. Biomass ethanol fuel cycles show significantly lower (up to 70%) and in some studies negative net carbon dioxide emissions (due to electricity credits). Carbon sequestration during plant growth and land use changes, relatively lower use of fertilizers and pesticides compared to corn, and credits for co-produced electricity account for significantly lower net carbon dioxide emissions. However the estimates vary significantly due to subjectivity in assessing co-product allocations, electricity credits, land use sequestration estimates and technology projections.

Conventional air pollutant emissions:

Large variations are observed in conventional pollutant emissions estimates across studies. In general, the conventional pollutant emission patterns are similar to the patterns for energy efficiency. The less energy efficient ethanol and biodiesel cycles showing significantly higher CO, SO₂ and NO_x emissions relative to conventional gasoline and diesel. NO_x emissions are also higher for biofuels due to fertilizer use. For obvious reasons, methane emissions for the natural gas based fuel cycles are significantly higher than all other fuel cycles ranging from 200% to 300% of gasoline fuel cycle. The corn ethanol cycle methane emissions are about 50% higher than the gasoline cycle. Lowest methane emissions are observed with bioethanol cycles.

CONCLUSION

Fuel cycle analysis of alternative fuels requires a complex accounting model attempting to keep track of a large number of interdependent products, processes and associated environmental impacts. Subjective judgements have to be made about boundaries of analysis, co-product allocation, future scenarios, technology trends etc. As a result, though the general structure of models for alternative fuel cycle analyses is similar across studies, the final estimates of energy use and emissions per GJ of fuel delivered to the vehicle vary significantly across different studies. However, some general patterns can be observed in relative performance.

The conventional gasoline fuel cycle has robust advantages with respect to energy efficiency, conventional pollutant emissions, and most importantly, established infrastructure compared to alternative fuels. Fossil fuel based alternatives like CNG, NG-Methanol, NG-FTD do not result in significant improvement in fuel cycle environmental performance. Biofuels offer the benefits of lower and even negative GHG emissions, sustainability, and domestic fuel production. The herbaceous and woody biomass-based ethanol options

are more attractive than producing ethanol and biodiesel from food products. The latter crops are more energy and input intensive and a feasible fuel production requires a high demand for their co-products. Ethanol from herbaceous or woody biomass could replace significant fraction of the gasoline required for the light-duty fleet while supplying electricity as a co-product. While it is more expensive than gasoline, bioethanol would be attractive if significant reductions in GHG emissions were required, or if the price of gasoline increased sharply.

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TABLE 1: Fuel Cycle Environmental Impacts Of Alternative Fuels
(Ranges from existing studies)*

Fuel	Energy Efficiency**	Range of fuel cycle emissions grams/GJ at vehicle				
		CO	NOx	SO ₂	CH ₄	CO ₂ (kg)
Gasoline	79-88%	4-49	18-68	24-79	10 –115	11-19
Reform. Gasoline	77-83%	4-43	20-64	27-51	11- 89	11-21
Diesel	83-91%	3-40	10-51	18-44	6-90	6.3 –14.4
Low S Diesel	81%	22	31	21	83	16.4
NG-CNG	79-86%	4-32	17-60	15-37	103-317	7.2-14.3
NG-Methanol	59-63%	9-54	34-125	10-43	109-286	21.6-31.8
NG-FTD#	52-58%	42	52	10	110	38.8
Corn Ethanol	45-59%	95-265	140-487	91-163	4-182	42.8-75.3
Herb-Bio Ethanol	37-62%	140-250	20-213	(8)-30	18-68	(7.7) -11
Wood-Bio Ethanol	47-68%	8-250	20-176	(60)-30	(33)-68	(3.9) –11
Soy-Biodiesel	69%	57	96	24	52	22.3
Electricity US mix	23-29%	55-67	470-526	580-752	1-445	188-209

These are based on references [1][2][4][8][12][16][18][19] and authors' back calculations of fuel cycle emissions from reported total life cycle emissions including vehicle use emissions. We compiled data from the base case scenario in each study.

** Defined as energy content of fuel delivered to the vehicle/total energy input in the fuel cycle.

Only one study [18] has full fuel cycle models for NG-FTD and low sulfur diesel

Table 2. Biofuel Requirements to Replace 100 Billion Gallons of Gasoline¹: Near Term and Sustainable Production[9]

Fuel	Biosource ² Yield (bushel ³ or dry ton /acre/year)	Fuel Yield: Near Term ⁴ (gal. fuel/ bushel or dry ton)	Required Biosource (billion bushels or dry tons)	Land Required: Near Term Production (billions acres)	Fuel Yield: Sustainable Production ⁵ (gal. fuel/ bushel or dry ton)	Land Required: Sustainable Production (billions acres)
Corn Ethanol	125	2.6	46	0.37	0.85	1.1
Herb. Ethanol	5.75	80	1.5	0.26	63	0.33
Woody Ethanol	5.26	76	1.6	0.30	62	0.37
Soybean Biodiesel	36	1.4	55	1.5	0.81	2.6

1. Values in the table are to produce 120 billion gallons of ethanol or 75 billion gallons of biodiesel.
2. Biosource refers to corn, soybeans, or biomass corresponding to that required for the fuel produced.
3. Values for corn and soybeans are reported in bushels, those for herbaceous and woody biomass in dry tons biomass.
4. Near term refers to current corn ethanol and soybean biodiesel production and near term ethanol from herbaceous and woody biomass.
5. Sustainable production refers to no fossil fuel use throughout the entire fuel cycle.