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Net Energy and Carbon Flow Analyses of Four Pathways for the Utilization of Natural Gas as Automotive Fuel

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The development of the natural gas (NG) reserves of the Philippines has led to interest in the use of NG as an automotive fuel. Successful utilization of NG as a fuel for motor vehicles will lessen the country's dependence on imported petroleum while reducing air emissions, particularly that of CO_2 which is the predominant cause of global climate change. Net energy analysis (NEA) and carbon flow analysis (CFA) were used to compare four different pathways for NG utilization: (a–b) direct use as fuel in liquefied (LNG) or compressed (CNG) form; (c) conversion to methanol; and (d) conversion to electricity for electric vehicle (EV) or hybrid electric vehicle (HEV) propulsion. The assessment was performed using the GREET 1.5a fuel cycle inventory model to determine the best practical environmental option (BPEO) among the four alternatives. Model uncertainties were dealt with using sensitivity analysis. When the analysis was based on 1 MJ of fuel energy delivered to the refueling site, CNG was the BPEO, followed by the LNG, methanol, and electricity pathways. Due to the variability of fuel processing or conversion efficiencies, the difference between LNG and methanol was found minimal. Basing the analysis on 1 km traveled by the end-user vehicle, the differences in fuel economy of the end-user vehicles had a drastic effect on the assessment results. Electricity was found to be the BPEO, followed by methanol, CNG, and LNG. Establishing a definite ranking of the options, however, was difficult due to the high degree of uncertainty in vehicle fuel economy projections.

Keywords: Natural gas (NG), net energy analysis (NEA), carbon flow analysis (CFA), GREET 1.5a fuel cycle inventory model, best practical environmental option (BPEO), *and* alternative automotive fuels.

INTRODUCTION

The automotive transport sector of any modern economy contributes significantly to both energy consumption and greenhouse gas emissions. In the late 1990s, for example, road transport accounted for 13% of the Philippines' total primary energy consumption, and a proportionate share of greenhouse gas emissions (World Resources Institute 2000). This sector is also virtually completely dependent on petroleum as an energy source and is thus highly vulnerable to oil market fluctuations. The recent development of the natural gas (NG) reserves in the country has stimulated interest in the use of the gas as an automotive fuel: in part, to reduce the country's dependence on imported oil; and, in part, to reduce air emissions from road vehicles (Philippine DOE 2000, Philippine DENR 2000).

In spite of that, no specific pathway for NG-utilization has been identified. Direct utilization of NG, either in compressed (CNG) or cryogenically liquefied (LNG) form remains the most immediate option. Due to technical problems associated with distributing, dispensing, and storing CNG or LNG, however, conversion to methanol has been identified as the next best alternative. Methanol is a liquid fuel that is more compatible with existing vehicle technology than either CNG or LNG. Although the handling and storage of methanol is also much simpler, it is highly toxic in liquid or vapor form.

Thus, a fourth option is to use NG to generate electricity which can be tapped as a "fuel" by electric vehicles (EVs) or grid-connected hybrid electric vehicles (HEVs). This pathway has the advantage of using existing power distribution infrastructure; however, EV and HEV technology is not as mature as conventional internal combustion engine vehicle (ICEV) systems (Poulton 1994). Other alternative pathways not considered in this study include conversion to hydrogen, synthetic gasoline, or diesel oil (Wang and Huang 1999).

Comparison of different NG-utilization pathways based either on efficiency or environmental criteria is not a new concept. Energy analysis of NG-based fuel life cycles was attempted by Crane (unpublished material, 1991). More recent studies by Wang and Huang (1999), General Motors Corp. (GMC et al. 2001), and Tan and Culaba (2002) used the GREET life-cycle model developed by Argonne National Laboratory (Wang 1999).

OBJECTIVES

The purpose of this study was to use net energy analysis (NEA) and carbon flow analysis (CFA) to determine the best practical environmental option (BPEO) among the four alternative pathways for the utilization of NG as an automotive fuel, namely: (a) conversion to electricity; (b) direct use as LNG; (c) direct use as CNG; and (d) conversion to methanol.

THE GREET 1.5a MODEL

GREET (***G***reenhouse Gases, ***R***egulated ***E***missions, and ***E***nergy Use in ***T***ransportion) is a public-domain life-cycle inventory model for simulating a wide range of existing and anticipated energy vectors for automotive transport. The fuel cycles include conservative technologies (e.g., reformulated gasoline) as well as radical energy systems (e.g., hydrogen for fuel cell vehicles). Developed by Argonne National Laboratory (ANL) for the U.S. Department of Energy, GREET is coded in Microsoft Excel® and may be downloaded from *www.transportation.anl.gov.* GREET breaks down the full fuel cycle into three broad stages:

- *Feedstock Extraction Stage* – includes environmental impacts of all operations needed to extract and prepare the fuel raw material or feedstock.
- *Fuel Production Stage* – includes environmental impacts of all operations needed to convert the feedstock into the fuel product, and the movement of the fuel from the processing facility to the refueling point.
- *Vehicle Operation Stage* – includes direct emissions from vehicle use.

The feedstock and fuel stages are collectively known as the *upstream (well-to-pump) segment* of the fuel life cycle. Although GREET, by default, calculates emissions per vehicle-mile, in upstream analysis environmental impacts are normalized *per unit of fuel*. This basis is appropriate when

Table 1*. *GREET Inventory Parameters

Category	Model Parameters
Greenhouse Gases	CO_2, CH_4, and N_2O
Regulated Emissions	VOC, CO, NOx, PM_{10}, and SOx
Energy Use	Total, Fossil, and Petroleum Energy

Source: Wang (1999)

GREET focuses on greenhouse gases, specific air emissions, and energy inputs. Greenhouse gases are of interest due to global warming. Miscellaneous air emissions contributing to photochemical smog formation, acid rain formation, and direct toxicity effects are also included in the model. Energy demands are assessed by the model as a measure of natural resource depletion impacts. The fossil energy parameter measures the extent to which a fuel cycle is dependent on nonrenewable energy sources. The petroleum energy parameter is significant since it quantifies the degree to which an alternative fuel displaces demand for oil.

GREET is a spreadsheet-based input–output model utilizing basic material and energy balance (MEB) principles. Its computational structure has been described by Wang (1999); hence, only the salient features of the model are discussed here. GREET is structured around a "backbone" energy balance model consisting of a chain of energy conversion processes or transportation activities (Hocking 1999). This chain begins with a raw material that is progressively converted into useful form and eventually delivered to the end-user for vehicle propulsion use. Each stage in the chain typically requires additional *process energy* for operation. For example, a hydrogen liquefaction process converts a feedstock (gaseous hydrogen) into a finished product (liquid hydrogen). The process itself, however, requires the use of electricity and other auxiliary energy inputs which, together with the feedstock consumption, make up the total energy demand.

As used in the GREET model, *process efficiency* is defined as the ratio of the fuel value of the product to the total energy input into the processing stage:

$$E = NHV_P\,(NHV_F + PE)^{-1} \qquad (1)$$

where:

E = process energy efficiency
NHV_P = net energy value of product
NHV_F = net energy value of feedstock
PE = process energy requirement

The energy balance model that constitutes the core of GREET is expanded into a full inventory model through the use of emission factors, which predict the amount of pollutant per unit of energy (Nieuwlaar et al. 1996). Energy flows calculated in the model are simply multiplied by these factors to determine the quantities of the different air emissions discharged. In this study, only the CO_2 emission factors were used. These factors were determined based on stoichiometric principles using the carbon content of the fuel inputs.

MODELING FRAMEWORK AND ASSUMPTIONS

This study used the NEA and CFA, two streamlined forms of life cycle assessment (LCA), to evaluate and rank four NG utilization pathways based on environmental merit. The underlying principles of LCA (SETAC 1991; ISO 1997) were preserved in both NEA and CFA, but the procedure was facilitated by focusing on specified material or energy flows (Curran 1996). Both the NEA and CFA were performed using the GREET 1.5a model. Table 2 lists modifications made in the model inputs for this study. All other default model settings were maintained.

The streams which were evaluated on a life-cycle basis for this study include:

- *Petroleum Energy Input* (PEI) – the total petroleum-derived primary energy needed to deliver the specified functional unit of product or service. For automotive fuels, PEI also gives an indication of the extent to which an alternative fuel displaces oil demand.

- *Coal Energy Inputs* (CEI) – the total coal-derived primary energy needed to deliver the specified functional unit of product or service.

- *NG Energy Inputs* (NGEI) – the total NG-derived primary energy needed to deliver the specified functional unit. For NG derivatives, NGE is a measure of the overall efficiency of resource utilization.

- *CO_2 Emissions* (CDE) – the total quantity of CO_2 released into the atmosphere for every functional unit of product or service delivered. Because CO_2 is the predominant cause of global climate change, emissions of this gas

Table 2. Parametric Assumptions Used

Model Parameter	Value	Source
Projected Philippine power mix for 2009	45% Coal 16% NG 10% Oil 29% Others	Philippine DOE 2000
Camago-Malampaya NG net heating value	46 MJ/kg	
Power generation efficiency (NG combined cycle)	50–60%	GMC et al. 2001
Efficiency of NG liquefaction	87–93%	
Efficiency of NG compression	96–98%	
Efficiency of NG conversion to methanol	65–71%	
Energy usage of EVs and HEVs	0.77–1.13 MJ/km	Wang 1999
Energy usage of LNG and CNG vehicles	1.54–3.78 MJ/km	
Energy usage of methanol vehicles	1.34–3.24 MJ/km	

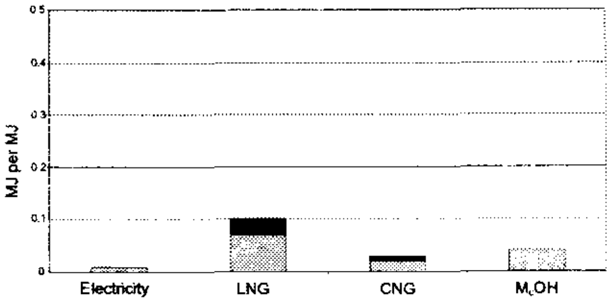

Figure 1. Petroleum Energy Inputs

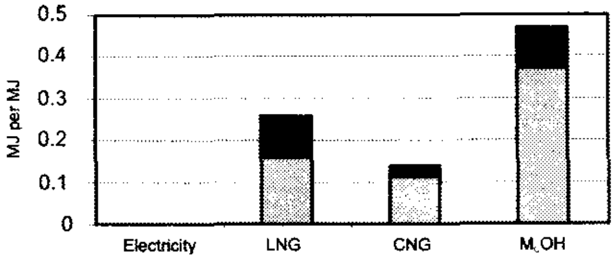

Figure 2. Coal Energy Inputs

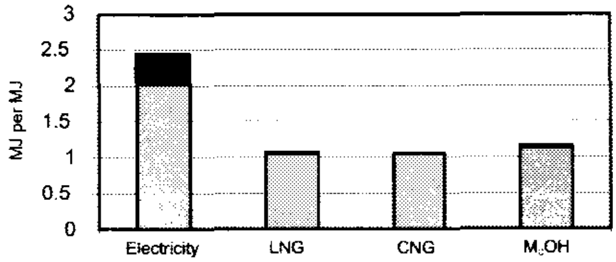

Figure 3. Natural Gas Energy Inputs

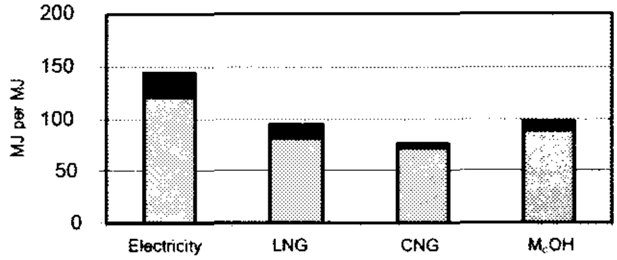

Figure 4. Carbon Dioxide Emissions

This study assessed energy and carbon flows based on the following functional units:

- 1 MJ of fuel energy delivered to refueling site, and
- 1 km traveled by the end-user vehicle.

RESULTS AND DISCUSSION

The life-cycle PEI, CEI, NGEI, and CDE results per megajoule of fuel delivered to the refueling site are given in Figures 1, 2, 3, and 4, respectively. The uncertainty margins are indicated by the dark bands in the histograms. On the one hand, both the PEI and CEI arise from the use of electricity and other auxiliary energy inputs throughout the fuel cycle, and are relatively small in magnitude. On the other hand, the NGEI and CDE values vary inversely with the overall life-cycle efficiency.

It is readily apparent from figures 3 and 4 that conversion to electricity is the least desirable alternative, primarily due to the relatively low efficiency of power generation vis-à-vis NG liquefaction, compression, or chemical conversion to methanol. Of the remaining three pathways, CNG is the most efficient, followed by LNG and then by methanol. The difference between LNG and methanol, however, is not significant.

The corresponding PEI, CEI, NGEI, and CDE values per kilometer traveled by the end-user vehicle are given in figures 5, 6, 7, and 8, respectively. These results have been adjusted to account for the fuel economy of the end-user vehicle. Based on figures 7 and 8, electricity is

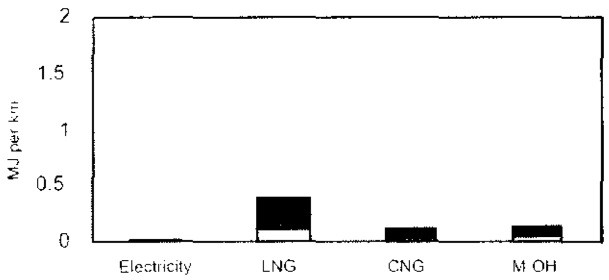

Figure 5. Petroleum Energy Inputs

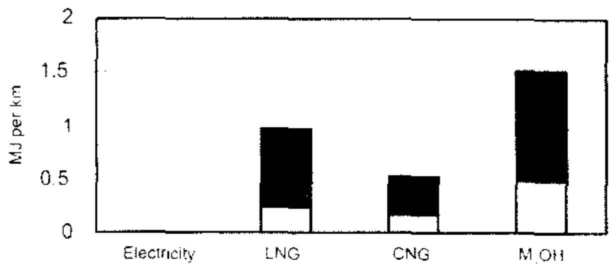

Figure 6. Coal Energy Inputs

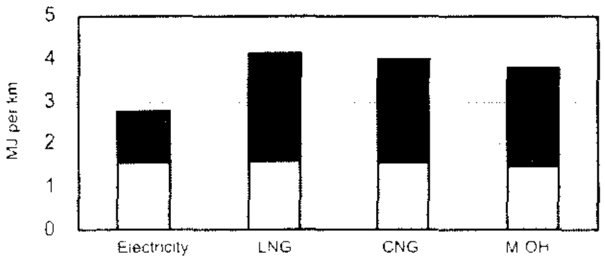

Figure 7. Natural Gas Energy Inputs

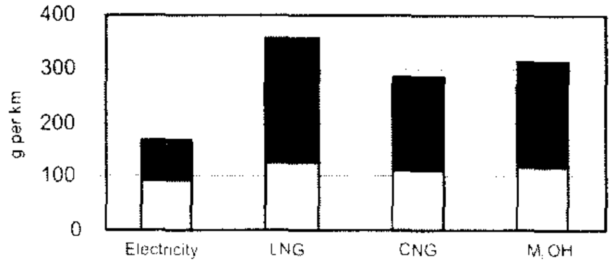

Figure 8. Carbon Dioxide Emissions

now the BPEO. Again, the PEI and CEI reflect only secondary energy inputs throughout the life cycles, and thus have minimal impact on the ranking of the options. The efficiency advantages of EVs and grid-connected HEVs over other vehicle types more than compensate for the upstream inefficiency of the electricity pathway. The ranking of the remaining three pathways (i.e., LNG, CNG, and methanol) is, nevertheless, indistinct because of the wide margins of uncertainty (indicated in the figures by the dark bands) in their NGEI and CDE results.

This uncertainty arises from the variety of possible vehicle technologies for utilizing these fuels. In general, the lowest fuel economy (and greatest environmental impact) results from the use of LNG, CNG, and methanol in flexible-fuel vehicles (FFVs) that can also run on gasoline. Better efficiencies are possible with dedicated-fuel internal combustion engine vehicles (ICEVs) designed to run specifically on LNG, CNG, or methanol. The best fuel economies, however, are achieved by NG- or methanol-powered HEVs and fuel cell vehicles (FCVs). Taking these factors into consideration, the CNG and methanol pathways are virtually identical in environmental performance, and both are slightly superior to the LNG option.

Figures 1 and 5 indicate that LNG requires significantly more PEI than the other alternatives because the cryogenic liquid must be transported, and quite inefficiently, in tankers. It is also evident in figures 2 and 6 that conversion to methanol requires the greatest indirect CEI (in the form of electrical power for processing).

Hence, from a purely environmental standpoint, the electricity and CNG pathways represent the two most promising means of utilizing NG as an automotive fuel. EV and HEV technology, however, is still relatively immature, making the electricity pathway unlikely in the Philippines in the immediate future. CNG and LNG likewise need massive changes in fuel distribution infrastructure and vehicle fleet technology to achieve significant market penetration. In the short term, methanol has the best prospect of being adopted because it is compatible with existing vehicle technology, particularly when used in gasoline blends.

CONCLUSIONS

The following can be drawn from the NEA and CFA results:

- On a per megajoule fuel-energy basis, the BPEO was determined to be CNG, followed by the LNG, methanol, and electricty pathways. The relative rankings were determined primarily by the upstream fuel-cycle efficiency. The superiority of LNG to methanol is not significant when variability of conversion efficiencies are accounted for.

- On a per vehicle-kilometer basis, the BPEO was determined to be electricity, followed by CNG, methanol, and LNG. The superiority of CNG to methanol is marginal. The relative rankings are highly dependent on vehicle fuel economy as well as on upstream fuel-cycle efficiency. Nevertheless, since some of the vehicle technologies considered are still in their infancy, the results remain highly speculative.

NOMENCLATURE

BPEO	best practical environmental option
CDE	carbon dioxide emissions
CEI	coal energy input
CFA	carbon flow analysis
CNG	compressed natural gas
EV	electric vehicle
GREET	***G**reenhouse Gas, **R**egulated **E**missions and **E**nergy Use in **T**ransportation*
HEV	hybrid electric vehicle
ICEV	internal combustion engine vehicle
LCA	life-cycle assessment
LNG	liquefied natural gas
NEA	net energy analysis
NG	natural gas
NGEI	natural gas energy input
PEI	petroleum energy input

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