Philippine Engineering Journal (2002) XXIII (1): 45-58

LIFE-CYCLE ENVIRONMENTAL BENEFITS OF USING BIOETHANOL AS A GASOLINE ADDITIVE

Raymond R. Tan, Ph.D.[a] and Alvin B. Culaba, Ph.D.[b]
[a]Chemical Engineering Department, De La Salle University
[b]Mechanical Engineering Department, De La Salle University
2401 Taft Avenue, Manila

ABSTRACT

Ethanol can be blended with gasoline as a fuel extender, an oxygenating agent, and octane enhancer. Blends containing up to 10% ethanol by volume (E10) can be used in unmodified spark-ignition engines without significant changes in vehicle performance, while yielding reductions in over-all tailpipe emissions. Enzyme-based processing technology is expected to allow ethanol to be produced commercially from cellulosic biomass such as municipal and agricultural waste as early as 2005. Ethyl alcohol produced in this manner is called bioethanol; this production technology promises to be an effective open-loop recycling ("waste-to-energy") pathway which simultaneously gives significant benefits of reduced fossil fuel consumption and air emissions. This paper presents results of simulations using a modified version of the GREET 1.5a fuel cycle model to estimate the relative benefits of using E10 instead of conventional gasoline. In addition to obvious savings in petroleum usage, reductions in life-cycle hydrocarbon, carbon monoxide, sulfur dioxide and carbon dioxide emissions are predicted by the model. Cumulative emissions of particulates and nitrogen oxides, on the other hand, are expected to increase.

Keywords: *Bioethanol, E10, Life Cycle Assessment (LCA)*

I. Introduction

In the aftermath of the oil shocks of the 1970s, the Philippines explored liquid biofuels as a means of insulating her economy from volatile petroleum prices. One of the fuels identified for development was bioethanol derived for sugarcane, which was used in gasoline blends called alcogas (Lorilla, 1982; Del Rosario et al., 1985). The alcogas program was also meant to provide alternative markets to revitalize the country's sugar production sector (Eala, 1985).

The alcogas program was abandoned in the mid-1980s due in part to domestic political turmoil, and in part to relatively stable international oil prices. Today biofuels such as ethanol merit reconsideration, but for different reasons:

- Bioethanol is a renewable energy sources that can offset usage of dwindling petroleum supplies (Cadenas and Cabezado, 1998). Based on recent reserves-to-production ratio statistics, the World's oil reserves will be exhausted in as little as forty years (BP Amoco, 2000)

- Bioethanol is an environment-friendly fuel that generate less emissions than conventional oil-based fuels when used in technologically similar vehicle propulsion systems (Clark and Howard, 2000; McCormack, 2000). In particular, bioethanol can give significant reductions in net carbon dioxide emissions, the predominant cause of global warming (Gustavsson et al., 1995; Dincer and Rosen, 1998; Sims, 2001)

- When used as E10 (alcohol-gasoline blend containing 10% ethanol by volume), bioethanol is compatible with the existing gasoline-powered vehicles. Unlike radical vehicle technologies such as electric drives or fuel cells, it can be used in existing spark-ignition (SI) engines without the need for major modifications (Poulton, 1994).

II. Bioethanol Properties and Production Technology

Properties of bioethanol relevant to its use as a motor vehicle fuel are given in Table 1. Corresponding figures for typical gasoline are provided for comparison purposes.

Table 1
Properties of Bioethanol and Unleaded Gasoline

Property	Bioethanol	Unleaded Gasoline
Chemical Formula	C_2H_5OH	C_4 to C_{12} chains
Oxygen Content (wt. %)	35	0
Road Octane Rating ([RON + MON]/2)	98 – 100	87.5 (minimum)*
Net Heating Value (MJ/kg)	26.7	41.8 – 44.1
Net Heating Value (MJ/l)	21.2	31.8 – 32.6
Density (g/ml)	0.79	0.72 – 0.78
Reid Vapor Pressure (atm)	0.16	0.61 (maximum)*
Stoichiometric Fuel-Air Weight Ratio	9	14.7
Flammability Limits (vol. %)	3 – 19	1 – 8

***based on specifications of the Philippine Clean Air Act (Philippine DENR, 2000)**

Early studies by the American Petroleum Institute (1976) and the United States Department of Energy (1979) identified the following key issues in the use of ethanol:

- Low flame visibility and poor detectability
- Proneness to water contamination
- Explosion hazard due to the flammability of ethanol-rich vapor-air mixtures
- Corrosivity towards some fuel system component materials
- Cold-starting difficulties (not relevant in Philippine climate)

- Reduced apparent fuel economy because of low energy content
- Food-or-fuel tradeoff (not relevant when cellulosic feedstocks are used)
- Negative net energy balance

Most of these problems are minimized by the use of gasoline-ethanol blends. The issue surrounding the negative net energy balance of ethanol applies for dedicated energy crops grown with energy-intensive agricultural practices. Energy requirements of integrated bioethanol production are minimized by using waste material as feedstock. Furthermore, non-fermentable components of the feed can be used as fuel to meet the thermal and electrical energy requirements of processing. Excess electrical power is available and can be exported from the processing facility for credits (Wang, 1999).

Production of bioethanol from cellulosic biomass using the enzymatic processes is described in detail by Kucuk and Demirbas (1997), McMillan (1997) and Borgwardt (1999). These processes have been tested on pilot plant scale and have proven technically feasible. Current processing costs are still prohibitive, but advances in biotechnology are anticipated to allow commercialization within the decade (Wang, 1999). The enzymatic production of bioethanol relies on enzyme action to chemically break down cellulose into fermentable sugars. Subsequent fermentation and alcohol refining is then possible using conventional technology. Recent evaluations of different alternative fuel options for the Philippine automotive transport sector concuded that fuels compatible with the existing vehicle fleet are the most viable options in the short term. Reformulated gasoline (RFG) was pinpointed by Colucci (2000) as particularly promising. One of the principal features of RFG is the presence of oxygenates – organic compounds containing bound molecular oxygen – to reduce vehicle emissions and improve fuel anti-knock characteristics (Poulton, 1994; Springer, 2000). Ethanol is highly oxygenated (35% oxygen by weight); E10 contains 3.7% oxygen, which exceeds typical requirements for RFG oxygen content (Wang, 1999).

III. Life Cycle Analysis

Life cycle analysis (LCA) is a holistic framework and methodology for assessing environmental effects of technological systems. It is distinguished by the following features:

- *Macrosystem or "cradle-to-grave" perspective* – LCA analyzes environmental interactions throughout the chain of activities supporting a given process or product technology. In the case of automotive fuels, LCA calculates emissions and environmental impacts emanating not just from vehicle exhaust emissions. Upstream impacts such as those generated during fuel production, transportation, storage and distribution are quantified as well. This is an important point since these "hidden" impacts may be quite signficant. For example, battery-powered electric vehicles (BEVs) generate no direct emissions during operation, but the electrical power used to charge their batteries may be generated in thermal power plants which actually produce combustion-related pollutants. Figure 1 shows the interaction of the life cycles of fuels and vehicles; the combined system is called the total energy cycle.

- *Multicriterion perspective* – LCA analyzes different pathways by which environmental damage is done. This approach gives a balanced scrutiny of both immediate or local impacts as well as long-term or global concerns. In cases where strong correlations exist among different environmental impacts, a single criterion can be selected as a representative index of environmental performance in order to simplify or "streamline" the analysis.

- *Functional unit perspective* – comparison and analysis of alternative technological systems is based on equivalency of service delivered (e.g., 1 vehicle-km of transportation service), rather than on the physical quantity of the final product.

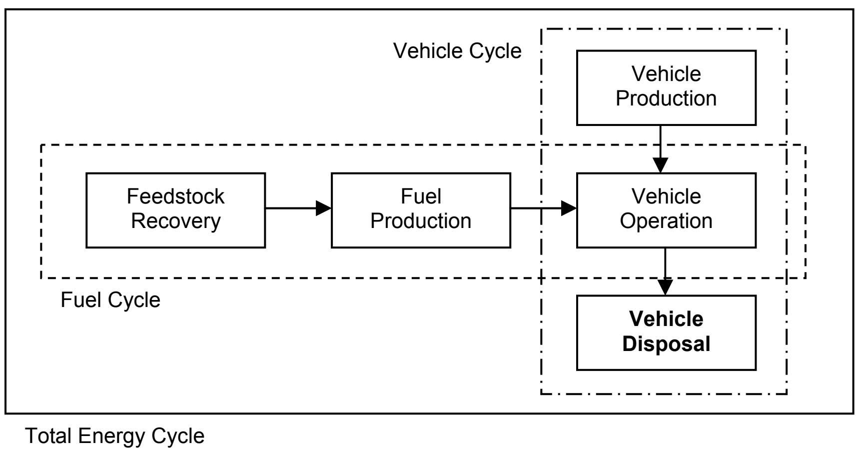

Figure 1. Fuel, Vehicle and Total Energy Cycles (Wang, 1999)

The emergence of modern LCA standards in the 1990s (SETAC, 1991; ISO, 1997; 1998; 2000a; 2000b) was characterized by an increase in the level of sophistication of the general life-cycle concept, which has now been extended to include four components for a full LCA. These components are:

- *Goal and Scope Definition* – specifies the objective of the assessment as well as the assumptions under which all subsequent analysis is done.

- *Inventory Analysis* – involves the quantification of environmentally relevant material and energy flows of a system using various sources of data. The data used may come from a variety of sources, including direct measurements, theoretical material and energy balances, and statistics from databases and publications. Quantification of pollutants is often sufficient to establish comparison between competing technologies.

- *Impact Assessment* – analyzes and compares the environmental burdens associated with the material and energy flows determined in the previous phase. Normalization and weighting (or valuation) of the impacts is also included in this stage. If necessary, the individual impacts can then be aggregated into a single composite environmental index.

- *Interpretation* or *Improvement Assessment* – utilization of the results of the preceding stages to meet the specified objectives.

IV. Modeling Framework and Assumptions

GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) 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 such as reformulated gasoline, as well as radical energy systems like hydrogen for fuel cell vehicles. Developed in Argonne National Laboratory (ANL), GREET is coded in Microsoft Excel® and is downloadable from the ANL website (Wang, 1999).

GREET breaks down the full fuel cycle into three broad stages:

- *Feedstock Recovery Stage*. Includes environmental impacts of all operations needed to extract and prepare the fuel raw material or feedstock.

- *Fuel Processing Stage*. Includes environmental impacts of all operations needed to convert the feedstock into the fuel product, as well as from the movement of the fuel from the processing facility to the refueling point.

- *Vehicle Operation Stage*. Includes direct emissions from vehicle use.

As its name implies, GREET focuses on greenhouse gases, specific air emissions, and energy inputs. Greenhouse gases are of interest due to concerns about 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 also assessed by the model as a measure of natural resource depletion impacts. The parameters accounted for in the basic model are described in Table 2.

Table 2
Environmental Parameters Simulated by GREET 1.5a (Wang, 1999)

Parameter	Description	Environmental Impacts
TE	Total energy demand per unit of fuel	Resource depletion
FE	Fossil-fuel energy demand per unit of fuel	
PE	Petroleum-derived energy demand per unit	
VOC	Volatile organic compounds excluding methane; also called non-methane hydrocarbons (NMHC)	Smog formation
CO	Carbon monoxide	Smog formation, toxicity
NO_x	Nitrogen oxides in NO_2 equivalents	Smog formation, rain acidification, eutrophication
PM_{10}	Particulates smaller than 10 microns	Toxicity
SO_x	Sulfur oxides in SO_2 equivalents	Rain acidification, toxicity
CH_4	Methane	Global warming
N_2O	Nitrous oxide	Global warming, stratospheric ozone depletion
CO_2	Carbon dioxide	Global warming
GHG	Total greenhouse gases (CH_4, N_2O and CO_2) in CO_2 equivalents.	

GREET is a spreadsheet-based input-output model utilizing basic material and energy balance (MEB) principles. A detailed description of its computational structure is given by Wang (1999); hence, only the salient features of the model need to be described 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 which 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). However, the process itself requires the use of electricity and other auxiliary energy inputs, which together with the feedstock consumption make up the total energy demand.

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

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

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.

GREET 1.5a is coded as a multidimensional Microsoft Excel file with the MEB calculations implemented through spreadsheet formulas and macros (Wang, 1999). It also contains an embedded database derived from an extensive literature review of relevant technical publications. One spreadsheet is allocated for each fuel but these interact with each other, as when one fuel is needed as an input in the production or processing of another fuel. For example, it is assumed that diesel is used in trucks that deliver the E10 to the refueling stations. The emissions of these diesel-powered trucks then become an indirect contributor to the over-all (life cycle) emissions of E10. Note that these interactions among the worksheets in the model may yield feedback loops. A more recent version of the model, GREET 1.6 (Wang, 2001) is coded in Visual Basic and features fully interactive graphical use interface (GUI) features, although the underlying computational model is essentially the same.

For this study, GREET 1.5a was recalibrated with the data in Table 3. Other default model settings were retained.

Table 3
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	
Average fuel economy of gasoline-powered vehicles	10 km/l	Assumed values
Average electrical power transmission loss	10%	
Utilization of processing residues for electricity credits	100%	
Energy requirements for biomass farming	0	

All simulation results are normalized based on 1 liter of fuel as the functional unit. Since the difference in fuel economy between gasoline and E10 is negligible (Poulton, 1994), for both fuels the functional unit utilized corresponds to 10 km of driving using the efficiency assumption in Table 3.

V. Results

5.1 Energy Inputs

Total, fossil fuel and petroleum energy requirements of the gasoline and E10 life cycles, normalized per liter of fuel, are given in Figure 2. The total energy requirement for E10 (42 MJ) is slightly higher than that of gasoline (40 MJ) due to the additional energy demands of bioethanol processing. This extra energy input, however, can be met using residual, unfermentable biomass as fuel. Hence, both fossil fuel (36 MJ) and petroleum energy (33 MJ) requirements of the E10 life cycle are lower than those of gasoline (39 MJ and 35 MJ, respectively).

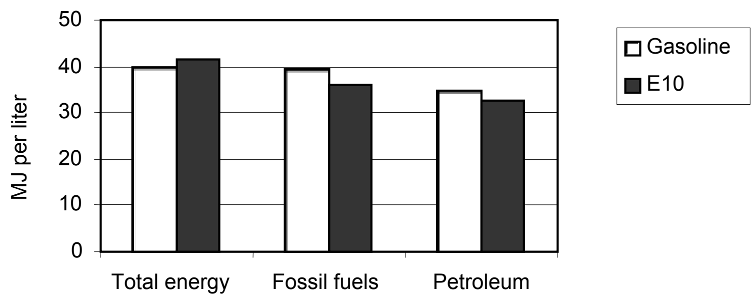

Figure 2 Life-Cycle Energy Inputs of Gasoline and E10

The corresponding energy profiles of vehicle operation are given in Figure 3. The total energy demand of both fuels is 31 MJ, reflecting the equal fuel economies of use. The fossil fuel (29 MJ) and petroleum energy (29 MJ) inputs of E10 are both lower than those of gasoline (31 MJ and 31 MJ, respectively) due to the partial displacement of the latter by bioethanol.

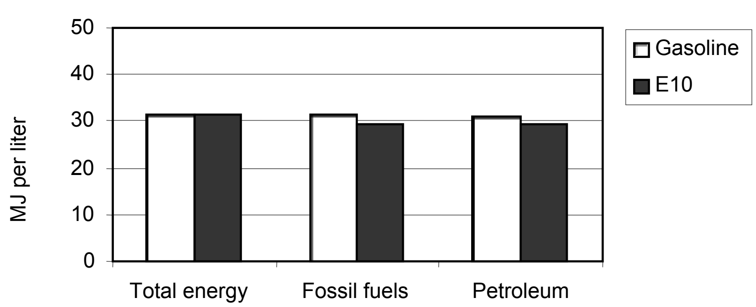

Figure 3 Vehicle Energy Inputs of Gasoline and E10

5.2 Air Emissions

Figure 4 shows the life cycle air emissions of E10 and gasoline. VOC, CO and SO_x emissions are 15 – 20% lower for E10 than for gasoline. On the other hand, NO_x and PM10 emissions are slightly higher for E10 because of the extensive use of biomass combustion to supply upstream energy demands in the scenario simulated.

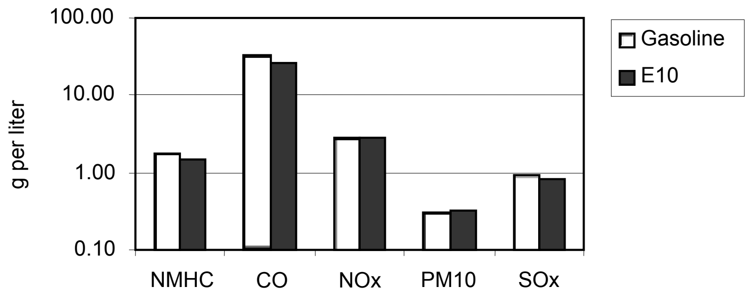

Figure 4 Life-Cycle Emissions of Gasoline and E10

Tailpipe emissions from vehicle operation are shown in Figure 5. Significant reductions in VOC, CO and SO_x emissions result from using E10 in place of gasoline. VOC emissions are reduced partly through decreased evaporative fuel losses (due to the relatively low volatility of bioethanol). Improved combustion due to the oxygen content of E10 reduces both VOC and CO exhaust emissions. Because bioethanol is virtually sulfur-free, blending in E10 automatically reduces SO_x emissions by about 10%. Vehicle PM_{10} and NO_x emissions are virtually identical for the two fuels.

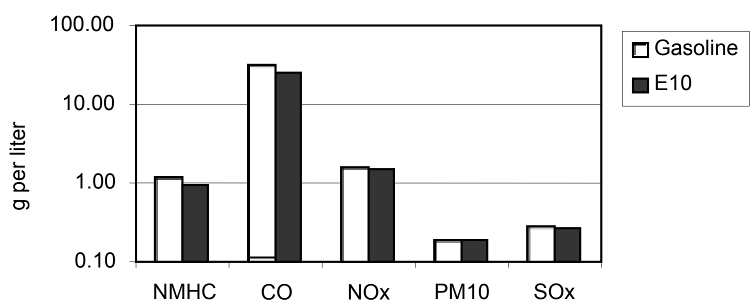

Figure 5 Tailpipe Emissions of Gasoline and E10

5.3 Greenhouse Gases

Life-cycle emissions of greenhouse gases are shown in Figure 6. Use of E10 gives reductions (relative to gasoline) of 6% for CH_4 and 11% for CO_2, while upstream combustion of biomass in bioethanol production results in a net increase of 12% in N_2O emissions. Because carbon dioxide accounts for 94 – 95% of global warming potential (GWP), the effects of CH_4 and N_2O emissions are almost negligible; E10 yields an 11% reduction in total greenhouse gases compared to conventional gasoline.

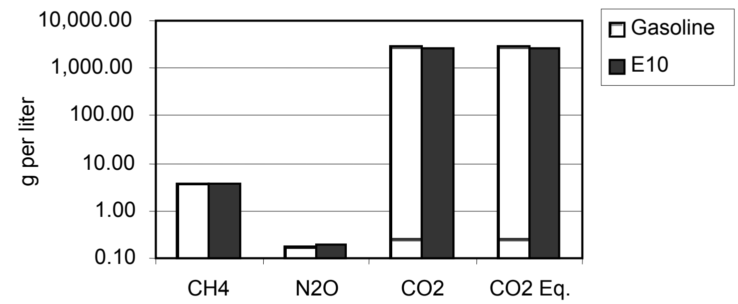

Figure 6 Life-Cycle GHG Emissions of Gasoline and E10

Figure 7 shows greenhouse gas emissions directly resulting from vehicle operation. There are reductions in CH_4 and CO_2 emissions that are roughly proportionate to the petroleum energy profiles in Figure 2. N_2O emissions of the two fuels are identical. Total greenhouse gas emissions are dominated by CO_2, which accounts for 97% of the total GWP of exhaust gases.

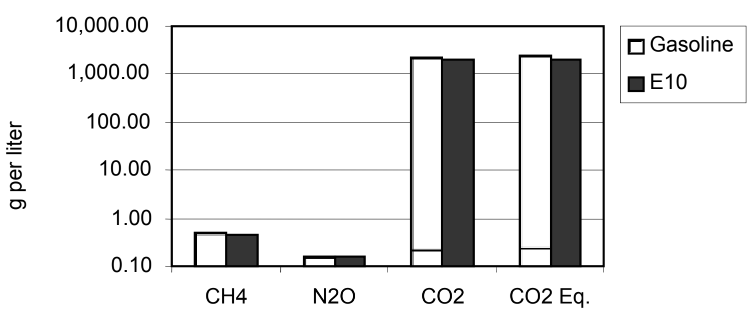

Figure 7 Tailpipe GHG Emissions of Gasoline and E10

5.4 Overall Costs and Benefits

Life-cycle benefits of E10 relative to gasoline are summarized in Figure 8. E10 gives improvements in eight of the twelve environmental parameters simulated by the GREET 1.5a model. The 6% reduction in petroleum energy indicates that bioethanol can be used to partially displace petroleum demand. In addition there are corresponding reductions in VOC (15%), CO (19%), SO_x (16%), CH_4 (6%) and CO_2 (11%) emissions. Total greenhouse gas emissions are also reduced by 11%.

The environmental penalties of E10 use are increases in NO_x (3%), PM_{10} (7%) and N_2O (12%) emissions due to the utilization of solid biomass as a fuel to meet the heat and electricity demands of bioethanol processing.

Figure 8 Relative Life-Cycle Benefits of E10 vs. Gasoline Use

In addition to environmental considerations, socioeconomic factors also play a role in determining the potential of E10 as a commercial fuel. A detailed discussion of these dimensions is beyond the scope of this paper, but in brief terms, the successful penetration of bioethanol into the Philippine fuel market is contingent on the following considerations:

- Provision of government subsidies, as in the case of Brazil's ProAlcool program. Subsidies can be justified as incentives for environmental benefits (Johansson, 1999) or energy supply security (Palmer, 1982). Alternatively, bioethanol production can be subsidized with funds generated from carbon emissions trading, once an international climate-change treaty is finalized (Babiker et al, 2000)

- Development of waste-to-energy schemes. Limited agricultural productivity and land area make dedicated energy crops impractical in the Philippines; however, both agricultural and municipal waste can be converted into bioethanol with anticipated technologies.

- Development of niche markets. Although total displacement of gasoline demand is unrealistic, bioethanol has potential as a specialty fuel or an octane-enhancing and oxygenating additive for RFG.

VI. Conclusions

The simulation results indicate that bioethanol use as E10 offers significant net environmental benefits over conventional gasoline. Although E10 use is predicted to increase particulate and nitrogen oxide emissions due to upstream biomass combustion for bioethanol production, these increases are offset by reductions in fossil fuel usage, petroleum consumption and all other air emissions analyzed. Furthermore, unlike radical propulsion technologies such as hydrogen and electric drives, E10 is compatible with the bulk of the existing Philippine vehicle fleet. The main obstacles to its commercialization are cost and public perception.

References

1. API Alcohols – "A Technical Assessment of their Applications as Fuels". American Petroleum Institute, Washington, D.C. (1976).
2. Babiker, M., Reilly, J. M. and Jacoby, H. D. "The Kyoto Protocol and Developing Countries". *Energy Policy* 28: 525 – 536. (2000).
3. Borgwardt, R. H. "Transportation Fuels from Cellulosic Biomass: A Comparative Assessment of Ethanol and Methanol Options". *Journal of Power & Energy* 213: 399 - 407. (1999).
4. BP Amoco *49th Statistical Review of World Energy*. London. (2000).
5. Cadenas, A., Cabezado, S. "Biofuels and Sustainable Technologies: Perspectives for Less Developed Countries". *Technological Forecasting & Social Change* 58: 83 – 103. (1998).
6. Clark, W. and Howard, R. S. "Renewable Energy Sources". *Proceedings of the Philippine Automotive Technology Conference and Workshop*, Makati City, Philippines. (2000).
7. Colucci, J. M."Options for 21st Century Automotive Fuels". *Proceedings of the Philippine Automotive Technology Conference and Workshop*, Makati City, Philippines. (2000).
8. Del Rosario, E. J., Chay, P. B., See, T. S., Deocadez, E. J., Moran, D. G. "Ethanol Production from Sugarcane and Sweet Sorghum". *Proceedings of the National Symposium on Renewable Energy Technologies*, Manila, Philippines. (1985).
9. Dincer, I., Rosen, M. "A Worldwide Perspective on Energy, Environment and Sustainable Development". *International Journal of Energy Research* 22: 1305 – 1321. (1998).
10. Eala, F. A, "Possible Long-Term Strategy for the Philippine Sugar Industry". *Proceedings of the National Symposium on Renewable Energy Technologies*, Manila, Philippines. (1985).
11. Gustavsson, L., Borjesson, P., Johansson, B., Svenigsson, P. "Reducing Carbon Dioxide Emissions by Substituting Biomass for Fossil Fuels". *Energy* 20: 1097 – 1113. (1995).

12. Hocking, M. B. "Net Energy Expenditure: A Method for Assessing the Environmental Impact of Technologies". In: Schulze, P. C., ed. Measures of Environmental Performance and Ecosystem Condition. National Academy Press, Washington, D.C. (1999).
13. ISO 14040 Environmental Management – Life Cycle Assessment – Principles and Framework. *International Organisation for Standardisation*, Geneva. (1997).
14. ISO 14041 Environmental Management – Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis. *International Organisation for Standardisation*, Geneva. (1998).
15. ISO 14042 Environmental Management – Life Cycle Assessment – Life Cycle Impact Assessment. *International Organisation for Standardisation*, Geneva. (2000a).
16. ISO 14043 Environmental Management – Life Cycle Assessment – Life Cycle Interpretation. *International Organisation for Standardisation*, Geneva. (2000b).
17. Johansson, B. "The Economy of Alternative Fuels when Including the Cost of Air Pollution". *Tranportation Research* – Part D 4: 91 – 108. (1999).
18. Kucuk, M. M., Demirbas, A. "Biomass Conversion Processes". *Energy, Conversion & Management* 38: 151 – 165. (1997).
19. Lorilla, F. "The Philippine Alcogas Program". *Proceedings of the Regulatory Workshop on the Technology of Fuel Alcohol Production,* Los Banos, Laguna, Philippines. (1982).
20. McCormack, M. C. "Lessons Learned: U.S. and California Experience with Alternative Fuels". *Proceedings of the Philippine Automotive Technology Conference and Workshop*, Makati City, Philippines. (2000).
21. McMillan, J. D. "Bioethanol Production: Status and Prospects". Renewa*ble Energy* 10: 295 – 302. (1997).
22. Nadim, F., Zack, P., Hong, G. E., Liu, S. "United States Experience with Gasoline Additives". *Energy Policy* 29: 1 – 5. (2001).
23. Nieuwlaar, E., Alsena, E. and van Engelenburg, B. "Using Life Cycle Assessment for the Environmental Evaluation of Greenhouse Gas Mitigation Options". *Energy Conversion and Management* 37: 831 – 836. (1996).
24. Palmer, D. G. "Biomass Fuels for Energy Security: A Policy Statement Concerning National Needs and Opportunities". *In: Progress in Biomass Conversion,* Vol. 3 (Sarkanen, K., Tillman, D. A., Jahn, E. C., eds.), Academic Press, New York. (1982).
25. Philippine Department of Energy Philippine Energy Plan 2000 – 2009. Manila. (2000).
26. Philippine Department of Environment and Natural Resources Implementing Rules and Regulations of RA 8749 – Clean Air Act of 1999. Manila. (2000).

27. Poulton, M. L. "Alternative Fuels for Road Vehicles". Computational Mechanics Publications, Southampton. (1994).
28. Rossillo-Calle, F., Cortez, L. A. B. **"** Towards ProAlcool II: A Review of the Brazilian Bioethanol Program**"**. *Biomass & Bioenergy* 14: 115 – 124. (1998).
29. Sims, R. E. H. "Bioenergy – A Renewable Carbon Sink". *Renewable Energy* 22: 31 – 37. (2001).
30. Society for Environmental Toxicology and Chemistry A Technical Framework for Life Cycle Assessments. Washington, D.C. (1991).
31. Springer, K. J. "The Relevance of Reformulated Fuels to Reduced Vehicle Emissions". *Proceedings of the Philippine Automotive Technology Conference and Workshop*, Makati City, Philippines. (2000).
32. US DOE The Report of the Alcohol Fuels Policy Review. United States Department of Energy, Washington, D.C. (1979).
33. Wang, M. "GREET 1.5 – Transportation Fuel Cycle Model". *Final Report ANL/ESD-39*, Argonne National Laboratory, U.S.A. (1999).
34. Wang, M., "Development of GREET 1.6 Fuel Cycle Model for Transportation Fuels and Vehicle Technologies". *Final Report ANL/ESD/TM-163*, Argonne National Laboratory, U.S.A. (2001).