Paper No. ESC-73

Sustainability Assessment Using Dynamic Systems Modelling

Albert W. Chan, David E. Minns
National Research Council of Canada, Ottawa, Canada

Bert McInnis, Robert Hoffman
Robbert Associates, Ottawa, Canada

ABSTRACT

A dynamic systems modelling approach is examined for its suitability for assessing sustainable performance in technological innovation. A computer model of the energy needs in the Canadian road transportation sector was developed to study the sustainable performance of bio-ethanol. It considers the potential increase in the consumption of energy as the economy expands in the next 25 years, taking into account demographic trends, consumer choices, and technological advances. While the primary environmental measure tracked is focused on greenhouse gas emissions with respect to the Kyoto target, it also includes considerations for land use and farming practices, and distinguishes between fossil and bio-carbon emissions. As well, it allows for different sources of biomass, including crop byproducts and dedicated crops. Various scenarios for bio-ethanol to penetrate the consumer market were set up to investigate a range of future evolution paths.

INTRODUCTION

Progress and development has often been linked with economic growth. While this view is sensible in that economic advances can lead to higher standard of living through improvements in basic needs such as housing, education and health care, environmental problems are also a common consequence of economic growth. Thus the quality as well as the quantity of growth needs to be addressed. Economic expansion can overwhelm gains in efficiency, leading to a greater total environmental impact in spite of technological advances in production, for example. Therefore the concept of development has to be broadened to include the environmental and the human dimensions, suggesting that economic growth must be balanced with social and environmental concerns. Sustainable development addresses this triple bottom line.

A commonly used goal of sustainable development is given by the Brundtland Commission – "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." There are two clear implications: sustainable development is a systems concept, and it is also a dynamic concept. In order to study the sustainability of a product, process or technology, it is necessary to examine the future evolution path of a socio-economic system, resulting from human activities and societal choices. From an environmental perspective, this means issues such as land use, air quality, clean water and biodiversity need to be addressed.

The Environmental Management Office at the National Research Council of Canada has been involved in the assembling of a tool set to assess the environmental and sustainable development performances of technologies and processes. A dynamic systems modelling approach was tested using the *whatIf?*® * tool, which has specific capabilities for developing dynamic models for policy analysis and decision support. A case study was performed on the use of bio-ethanol as an alternate fuel for road transportation in Canada.

ROAD TRANSPORTATION IN CANADA AND BIO-ETHANOL

Emissions of greenhouse gases (GHG) from Canadian road transportation sources amount to about 20% of the total greenhouse gas emissions in Canada, and about 75% of the emissions in the transportation sector. Canadians use 38 billion litres of gasoline in their vehicles each year. The average Canadian passenger vehicle, driven 100 km at highway speed, consumes nearly 12 litres of gasoline. Its tailpipe emits unburned chemicals and gases, smog-forming nitrous oxides, sulphur compound and microscopic soot particles. These emissions are toxic, carcinogenic or damaging to highly sensitive lung tissues. It is estimated that nationally, up to 16,000 deaths are attributed to air pollution each year.

It is reported that there are now 18 million vehicles in Canada. New vehicle growth is outpacing population growth and new housing construction. The vehicle growth rate is making cars and trucks a primary culprit for greenhouse gas emissions. It is growing fastest in urban areas, where more vehicles are clogging area roads and suburban sprawl is entrenching a car-dependent culture. It is evident that in a sustainable development context, any analytical study, including those for technology innovation, needs to take these demographic trends and societal choices into consideration.

It has been estimated that the reductions in emissions from the use of catalytic converters on cars, since they were introduced in the 1970s, are being cancelled out by a 250% increase in car use. As well, the average fuel efficiency of the North American car fleet has been falling due to increasing sales of less energy-efficient light trucks, minivans and sports-utility-vehicles (SUVs). These make up almost half of the national passenger vehicle sales. They consume on average about 30% more fuel, thus costing correspondingly more to use as well as emitting more greenhouse gas than an average passenger vehicle.

Ethanol is being promoted as a cleaner, renewable alternative to gasoline. Because of ethanol's high octane and oxygen content (35%), the engine is expected to burn all fuels more completely, last longer, and give added acceleration. The production and use of renewable fuels manufactured from lignocellulosic agricultural feedstocks, such as switchgrass and hay, or agricultural byproducts such as straw and corn stover, provide an opportunity to reduce greenhouse gas emissions and offer synergistic benefits to the agricultural and transportation sectors. Ottawa-based Iogen currently has the largest cellulose-to-ethanol producing plant in the world.

The Iogen process is known as an enzymatic hydrolysis process in which enzymes are used to convert cellulose and hemicellulose to fermentable sugars. Prior to the hydrolysis, the feedstocks are pre-treated with a modified steam explosion step to increase the accessibility of the fibre so that fewer enzymes are required for the hydrolysis step. After pretreatment the substrate passes to hydrolysis vessels for conversion of the cellulose and hemicellulose fibres to glucose and pentose sugars. A portion of these sugars is used to produce the enzymes for hydrolysis and the remainder is sent to the fermenters for the conversion of pentose sugars to ethanol.

Even though the use of bio-ethanol blended with gasoline is expected to reduce tailpipe emissions, the entire life cycle must be considered if the system performance of this biotechnology is to be assessed for sustainable development. The environmental implications from feedstock cultivation, to transporting the biomass, to producing the bio-ethanol, to the fuel efficiency when used in traditional car engines, etc. all need to be included. Whereas a Life Cycle Analysis on bio-ethanol will help to assess the environmental impacts under various categorizations and to reveal the hot spots based on one vehicle-kilometer travelled, it answers only the question "Is bio-ethanol cleaner?" but not the question "Is bio-ethanol clean enough?"

In 1997, the parties to the 1992 United Nations Framework Convention on Climate Change (FCCC) adopted a protocol (the Kyoto Protocol) to the Convention to limit emissions of greenhouse gases. The Protocol will come into force when 55 countries, covering a minimum of 55% of the FCCC Annex 1 countries emissions, have ratified the protocol. Canada is an Annex 1 country and has accepted a GHG reduction target of 6% below its 1990 level of 564 Mt (CO2 equivalents) by the end of the first reporting period, 2008-2012. Regardless whether Canada and a number of other countries will ratify the Kyoto Protocol, the reduction levels set by the protocol do lay out a tangible target to strive for in a sustainable development context.

DYNAMIC SYSTEMS MODELLING

The Dynamic Systems Modelling approach was examined for the purpose of assessing how technologies may help to achieve the goal of sustainability. This approach [1,2,3,4] recognizes that sustainability is a whole systems concept concerned with human activities in the context of the naturally occurring systems that provide the sources and sinks for the flows of materials and energy associated with them, and the ability of those systems to sustain human activities in the future. The starting point is the current state of the system: the stocks of artifacts that are the accumulated results of human activities and the state of natural systems as they have been impacted by human activities over time. The objective of the analysis is to determine whether the injection of new technologies or reconfigurations of human activities have implications on the sustainability of the trajectories that embody the hypothesized reconfigurations.

The whole systems concept implies that the systems being analyzed are finite or limited. The goal of sustainability is specified in absolute terms. For example, it is not sufficient to say that a particular technology reduces greenhouse gas emissions; it is necessary as well to say by how much the technology, if deployed over a stated period of time, will contribute to meeting an absolute target level of green house gas emissions. The concentration of greenhouse gases in the (finite) biosphere must be lower than a particular threshold if global warming is to be avoided. Thus the analysis of sustainability must take potentially critical limits into account.

In practical terms, it is necessary to limit the scope of analysis by bounding the number of processes to be included in the dynamic systems model. Where the systems boundary is drawn is arbitrary and may have significant impact on the conclusions arrived at. Thus care should be taken to include processes that might be limiting. For example, in the case of biofuel analysis, the land devoted to the production of the biomass feedstock may be limiting.

The key concept in Dynamic Systems Modelling [5,6,7,8] is that of process; a process transforms a time stream of input flows of materials, energy or information into a time stream of output flows. Processes may be naturally occurring or purposeful in the sense that they are designed and operated by humans to meet their needs. For the purposes of this analysis, it is helpful to think of the following categories of transformation processes: biological processes (production of biomass), extraction processes (mining, harvesting, logging, fishing), conversion processes (beneficiation, reduction of ores, alloying, chemical processing, and energy conversion), and manufacturing processes (fabrication, assembly and construction). While it is customary to think of a process as transforming raw materials and energy into products, the concept applies equally to consumption activities. For example, a house may be thought of as an artifact that is intended to provide conditioned space to its occupants.

The dynamic systems model developed for the analysis of sustainability of the use of bio-ethanol in transportation was implemented using *whatIf?*, a suite of modelling tools intended to support the design, implementation and use of process-based simulation models, with particular focus on systems involving interactions between human activities and the environment. These software tools feature an n-dimensional data-structured language for expressing model procedures using the syntax of subscripted algebra, a scenario and model manager that facilitates the creation of scenarios and manages linkages among models, and a case tool that uses structured diagrams for the documentation of model structure.

RELATED LIFE CYCLE ANALYSIS

"Life-cycle assessment is an objective process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and material usage and environmental releases, to assess the impact of those energy and material uses and releases on the environment, and to evaluate and implement opportunities to effect environmental improvements. The assessment includes the entire life cycle of the product, process, or activity encompassing extracting and processing raw materials; manufacturing, transportation and distribution; use/re-use/maintenance; and final disposal." This is the definition of life cycle assessments developed at a workshop on methods for performing life-cycle assessments held in August 1990, and sponsored by the Society of Environmental Toxicology and Chemistry [9].

Life Cycle Analysis (LCA), as it has come to be practiced, is focused on comparative analysis: what is the full environmental burden per unit product or per unit process flow over the entire life cycle of a given product or technology compared with another. It shares with the Dynamic Systems Modelling approach the idea of a systems boundary that encompasses all of the upstream processes that are implicated in the product or process, and calculates the environmental burden associated with them. But unlike the Dynamic Systems Modelling approach, Life Cycle Analysis abstracts from the context of time and space and hence cannot address the issue of sustainability and the full dynamics of the penetration of a new technology into the system.

Two LCA studies on bio-ethanol have been carried out by Levelton [10,11]. The use of corn, crop byproducts and dedicated crop (such as switchgrass) to produce bio-ethanol using the enzymatic hydrolysis method was investigated. The life cycle emissions for the cases of E10 (10% ethanol blended with gasoline) and E85 were compared with gasoline under different annual production volume scenarios of bio-ethanol and under two time frames (2000 and 2010). A spreadsheet approach was used, allowing for hypothetical scenarios of technological improvements in production and efficiency to be evaluated. However, the dynamic aspects of economic growth trends and evolution paths were not considered. Projected reductions in GHG emissions in the various cases were assessed against the Kyoto target.

BIO-ETHANOL CASE STUDY

The simulation model developed in this case study was designed to analyze and compare GHG emissions over a wide range of alternate engine technologies and fuel choices. It is intended to be “cradle to grave,” handling emissions associated with all the major processes, encompassing fuel production from resource base to “fuel in the tank,” as well as tailpipe emissions. The model can be viewed as comprising three modules.

The first module is adapted from a simulation model previously built by Robbert Associates for the Natural

Resources Canada (NRCan) Office of Energy Efficiency (OEE) to test the adequacy of their transportation energy demand database in support of the analysis of transportation sector energy demand into the future. That simulation model addresses vehicle stock energy demand and contains a significant representation of consumer choices. The data used in the NRCan model were carried over into the present model.

In this module, personal use vehicle stock is sized by household count and household ownership rates. Commercial use vehicle stock is sized by real domestic product (RDP). Household count and RDP are exogenous variables. Vehicles are simulated in one-year vintages over time by vehicle class and engine type with the starting age distribution determined by calibrating the model over historical time. Personal use vehicles are classed by small car, large car and light truck (SUV, etc.), while commercial use vehicles are classed by small car, large car, light truck, medium truck and heavy truck. Vehicle characteristics such as fuel economy and emissions are engine-class and year-built specific, whereas vehicle use is class and vehicle-age specific. Dual fuelled vehicles, like those with gasoline engines, can be fuelled by a range of fuel choices.

Based on given demographic trends represented by the number of households, number of vehicles per household, vehicle kilometer travelled (VKT), etc., the energy demand of the transportation sector needed to support these trends is computed.

A second module to compute the emissions based on the energy demand determined in the first module was then developed. Emissions related to the manufacture and operation of the vehicles, emissions related to the extraction, refinery, transportation, storage and distribution of the gasoline required, emissions related to the production of bio-ethanol, mixing with gasoline, and distribution to consumers are all computed based on emission coefficients in this module. Ethanol may be produced from biomass from dedicated crop, crop byproduct (residue), and municipal waste. In the scenarios reported in this paper, ethanol is produced from cropland byproduct, thus there is no trade-off between food production and ethanol production.

A third module was added to model the supply of biomass needed to produce the bio-ethanol demanded under various scenarios. Agricultural land, both crop-producing and non-crop-producing, is accounted for and the carbon stocks in those lands are simulated. In the simulation of crop production, additional fertilizer is required to offset the biomass extracted from the cropland to support ethanol production. GHG emissions related to crop cultivation and harvest, and fertilizer application and production are computed. As well, a farm land model was developed to capture the carbon cycle activities and the implications of farming practices as they impact on atmospheric carbon and soil carbon concentrations.

The sources of the data used for calibration of the present model are the following:

1) NRCan OEE Transportation Database [12]:
    - Household and RDP data
    - Vehicle stocks
    - Fuel efficiencies
    - Vehicle Kilometer Travelled
2) Statistics Canada Agricultural Census [13,14,15]:
    - Land stocks
    - Crop land seeded and yields
3) Agriculture Canada [16]:
    - Payload and root mass ratios
4) Levelton Engineering Ltd. [10,11]:
    - Process data coefficients for fuel production
    - Process GHG-emission coefficients.

SCENARIOS MODELLED

Although the underlying simulation model developed to support this analysis can handle a much wider range of engine technologies, this study deploys only the gasoline and E85 engines. Two fuelling choices for the gasoline engine, pure gasoline and E10, were considered. The 3 scenarios compared are:

<u>Scenario 1</u>: Pure gasoline fueling of gasoline-engined vehicles throughout simulation time.

<u>Scenario 2</u>: Pure gasoline fueling of gasoline-engined vehicles at the beginning of the scenario, linearly phasing into pure E10 fueling by year 2011.

<u>Scenario 3</u>: The new vehicle share of E85 engines for small car, large car and light truck vehicle classes is phased in from 0% at the scenario start to 100% in the year 2011, while the new share for gasoline engines is phased out from 100% in the scenario start to 0% in the year 2011. Existing gasoline-engined vehicles are fuelled according to Scenario 2.

In each of these three scenarios, the same transportation service measured in vehicle kilometers by vehicle class is delivered to the personal use and commercial use sectors. Based on the historical trends, projected trends for household count, new vehicle share by vehicle class, as well as the growth in VKT for personal use vehicles are assumed. Fuel demand is determined by applying vehicle-class year-built specific fuel economies for the total VKTs for each vehicle class by engine type in the stock at any time. Credit is given for the improved energy efficiency for using ethanol. Tailpipe emissions are determined by applying year-built specific emission rates to the total VKTs for each vehicle class by engine type in the stock at any time.

The last two scenarios will respectively demand a larger supply of bio-ethanol for fuel, and will in turn lead to a higher off land use of crop biomass. In the scenarios reported in this paper, there is just sufficient cropland byproduct to produce the required ethanol out to the year 2028.

SIMULATION RESULTS

GHG emissions (measured as CO2 equivalent) for 18 process sectors are determined in the model by bio and fossil sources. Figure 1 shows the total net emissions for the 3 scenarios, along with the Kyoto target (6% below 1990 emissions). In the net emissions calculation, the standard credit is taken for CO2 implied by producing ethanol from a bio source. These figures do not show any of the soil-based emissions computed in the model.

For Scenario 1, emissions rise rapidly starting at the beginning of the scenario period compared to the relatively flat behaviour in the late historical period, which is a result of the post OPEC shock response of substituting small cars for large and an overall increase in engine efficiency. However that process has worked its way through the stock by the end of the historical period, and efficiency stays more or less flat. This, coupled with the rising share of light trucks and the increasing amount of transportation service required by the economy, explains the apparent growth discontinuity between the history and scenario periods.

In Scenario 2, emissions do not rise as fast as in Scenario 1 until the year 2011, when the substitution of E10 fuels for gasoline is complete. The pressure of economic growth and growth in the number of households continue to create increases in emissions. In Scenario 3, a flattening of emissions due to the marginal substitution of E85 engines is observed, which saturates at 100% by 2011. The pressure of economic growth eventually turns the emissions curve around, and again, emissions continue to rise but are at an overall lower level.

It is noted that none of these scenarios come close to meeting the Kyoto target (flat line at the bottom, representing 94% of the 1990 5-year rolling average). In fact, in the best of these three scenarios, total net emissions are still about 33% above the Kyoto target in 2011.

CONCLUSIONS

As one of the key objectives of the case study is to evaluate the suitability of the Dynamic Systems Modelling approach for studying sustainable development performances of technologies, the present model does provide some useful insight. The approach appears to be well suited to studies where it is necessary to look at trends of future development, economic growth and demographics. A modelling tool such as *whatIf?* offers many features to facilitate the simulation of the dynamics of these trends. Where a multiplicity of trends and projections are involved, the Dynamic Systems Modelling technique has a definite advantage over static modelling and spreadsheet approaches for analysis. As well, the simulation enables the various possible migration paths to reach certain targets to be revealed, providing valuable insight as to “how to get from A to B” in a sustainable development context. However, these advantages do come with a cost – a rather steep learning curve. A substantial investment of time and resources is needed to become familiar with the tools and technique in order to do a comprehensive analysis. While the simpler, static spreadsheet model may cost less to develop, it falls short in providing the capabilities needed to analyze those dynamic aspects often crucial to the assessment of sustainable performance.

While the sustainability of bio-ethanol as an alternate fuel has been taken as a focus of the case study in the present model, it was designed with enough structure so that a range of issues, such as greenhouse gas emissions, land use, future trends for fuel demand, possible means to supply the biomass to produce the bio-ethanol, farming practices, etc., can be investigated. The objective is not to make a definitive assessment of the sustainability of bio-ethanol, but to ascertain the suitability of the Dynamic Systems Modelling approach for studying systemic, sustainable performance in technology innovation. It is worth noting that the same model could be used to analyze a wide range of other technologies of interest for their impact on sustainable development. The model demonstrates that the interplay between environmental, economics and social issues need to be addressed simultaneously in analyzing sustainability.

On the issue of using bio-ethanol as an alternate fuel in transportation, preliminary findings point to the fact that with the current trends of expansion of the economy and societal choices, even with an aggressive substitution program to use bio-ethanol, the Kyoto target for greenhouse gas reduction will be difficult to meet without the help of other government policies and measures, as well as changes in consumer behaviour. Aggressive promotions have led to the increasing sales of light trucks and SUVs. The consequence has been a lowering of fuel efficiency and a rise in energy consumption. In the Canadian context, besides switching to bio-ethanol, these consumer trends need to be turned around in order to have a chance of achieving the Kyoto target.

REFERENCES

[1] Hoffman, R., B. C. McInnis and W. S. Page, "Process Analysis" in *The Encyclopedia of Materials Science and Engineering,* M.B. Bever, editor-in-chief, Pergammon Press. 1986.

[2] Gault, F.D., K.E. Hamilton, R.B. Hoffman, and B.C. McInnis, "The Design Approach to Socio-Economic Modeling", *Futures*, February, 1987.

[3] Ayres, R. U., *Resources, Environment and Economics: Applications of the Materials/Energy Balance Principle*, Wiley, New York, 1978.

[4] Checkland, Peter, *Systems Thinking, Systems Practice*, John Wiley and Sons, Toronto, 1981.

[5] Capra, Fritjof, "Criteria of Systems Thinking", *Futures*, October, 1985.

[6] Gault, F.D., K.E. Hamilton, R.B. Hoffman, and B.C. McInnis, "The Design Approach to Socio-Economic Modeling," *Futures*, February, 1987.

[7] Gault, F.D., R.B. Hoffman, and B.C. McInnis, "The Path to Process Data," *Futures*, October, 1985.

[8] Georgescu-Roegan, Nicholas*, The Entropy Law and the Economic Process*, Harvard University Press, Cambridge, 1971.

[9] Society of Environmental Toxicology and Chemistry (SETAC). *A Technical Framework for Life-Cycle Assessment*, the report of a workshop held at Smugglers Notch, Vermont, August 1990, SETAC Foundation, January 1991.

[10] Levelton Engineering Ltd., *Assessment of Net Emissions of Greenhouse Gases from Ethanol-Gasoline Blends in Southern Ontario*, Agriculture and Agri-Food Canada, August 1999.

[11] Levelton Engineering Ltd., *Assessment of Net Emissions of Greenhouse Gases from Ethanol-Gasoline Blends in Canada: Lignocellulosic Feedstocks*, Agriculture and Agri-Food Canada, December 1999.

[12] Natural Resources Canada, Office of Energy Efficiency, Transportation Energy Demand Database.

[13] Statistics Canada, *Human Activity and the Environment 2000* (Catalogue No. 11-509.XPE), 2000.

[14] Statistics Canada Agricultural Census, *Field Crop Reporting Series*, 1987 – 2000.

[15] Statistics Canada Agricultural Census, *Grain Trade of Canada*, 1987 – 1998.

[16] Dr. Henry Janzen, Lethbridge Research Centre, Agriculture and Agri-Food Canada, Lethbridge, Alberta.

* *whatIf?*® is developed and owned by Robbert Associates Ltd. (*www.robbert.ca*)

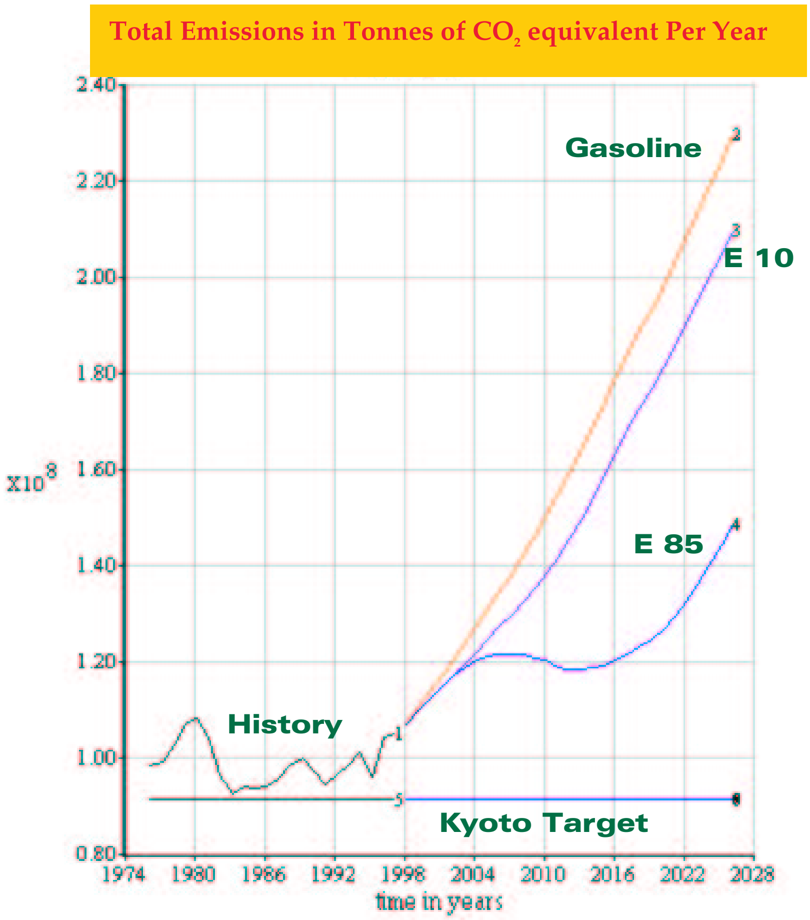

Figure 1: Net GHG Emissions and the Kyoto Target