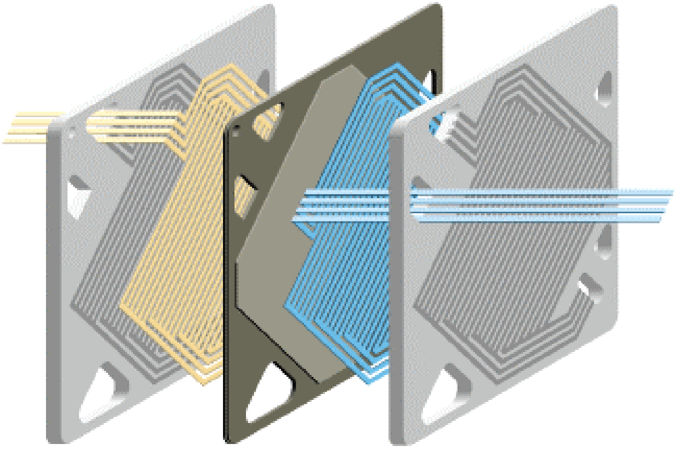
Climate-Friendly Hydrogen Fuel:

A Comparison of the Life-cycle
Greenhouse Gas Emissions for Selected
Fuel Cell Vehicle Hydrogen Production Systems



prepared by
The Pembina Institute

Pembina Institute
for Appropriate Development

with support from
The David Suzuki Foundation

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Finding solutions

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The Pembina Institute is an independent, citizen-based environmental think-tank specializing in the fields of energy-environment, climate change and environmental economics. The Institute engages in environmental education, policy research and analysis, community sustainable energy development and corporate environmental management services to advance environmental protection, resource conservation, and environmentally sound and sustainable resource management. Incorporated in 1985, the Institute's head office is in Drayton Valley, Alberta with additional offices in Ottawa and Calgary and research associates in Edmonton, Vancouver Island and other locations across Canada.

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The David Suzuki Foundation is a federally registered Canadian charity that explores human impacts on the environment, with an emphasis on finding solutions. We do this through research, application, education and advocacy. The Foundation was established in 1990 to find and communicate ways in which we can achieve a balance between social, economic and ecological needs.

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About this Report

This report was prepared by the Eco-efficient Technologies Program staff of the Pembina Institute, using a streamlined version of the Institute's Life-cycle Value Assessment Methodology. Financial support and technical advice were provided by the David Suzuki Foundation and by the Pembina Institute. The project is a joint effort of the Pembina Institute and the David Suzuki Foundation to ensure that public policy-makers and transportation industry leaders understand the importance of hydrogen fuel life-cycle emissions, and select fuel systems that realize the environmental promise of the hydrogen fuel cell technology, including the reduction of greenhouse gas emissions. The primary authors of this report were Yori Jamin and Marlo Raynolds of the Pembina Institute, with support and editorial assistance from: Mark Brownlie, Stephanie Cairns, Rob Macintosh, Matt McCulloch, Kim Sanderson, and Gary Woloshyniuk of the Pembina Institute, and Dermot Foley and Gerry Scott of the David Suzuki Foundation.

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Cover graphic: Single Ballard Fuel Cell, courtesy of Ballard Power Systems

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Executive Summary

Increasing demand for vehicles with low tailpipe emissions, high fuel efficiency and immediate throttle response make the hydrogen fuel cell an ideal alternative to the internal combustion engine. Industry proponents and governments have also pointed to the fuel cell as a key technology to reduce vehicle emissions of greenhouse gases responsible for climate change, as vehicles are one of the largest and fastest-growing emission sources. However, energy is used and greenhouse gases are produced "upstream" from the vehicle fuel cell itself, to produce, store and transport hydrogen.

The actual greenhouse gas reduction benefit of shifting to the hydrogen fuel cell therefore depends heavily on the amount of carbon dioxide, methane and nitrous oxide released in the manufacture and delivery of the hydrogen fuel. These emissions can be expected to vary tremendously among the different industrial processes for producing hydrogen. Securing a climate-friendly hydrogen fuel supply system means assessing the greenhouse gases produced across the entire fuel life cycle of potential hydrogen supplies, and comparing the results with a similar life cycle assessment of the fuel for a conventional internal combustion engine.

To determine the range of net greenhouse gas reductions available from various hydrogen supply systems, a life-cycle approach – Life Cycle Value Assessment (LCVA) – was applied to quantify the expected greenhouse gas emissions generated for five different sources. These options were then compared to the base case for current emission levels – a Mercedes-Benz A-Class vehicle powered by a gasoline internal combustion engine. The comparisons were done for the fuel needed to provide the common end-use service of traveling 1000 km. The five systems analyzed were:

1. On board reformulated gasoline fuel processing
2. On board methanol fuel processing
3. Centralized natural gas reforming
4. Decentralized natural gas reforming
5. Decentralized electrolysis

Other options do exist for producing hydrogen, including electrolysis using electricity from renewable resources or nuclear power, or on-board reforming of ethanol. While hydrogen produced from clean renewable-based electric power or from biomass-based ethanol would clearly be more climate friendly solutions over the long term, the five selected above are hydrogen supply systems vying for near-term fuel supply opportunities on the basis of cost and availability of existing infrastructure.

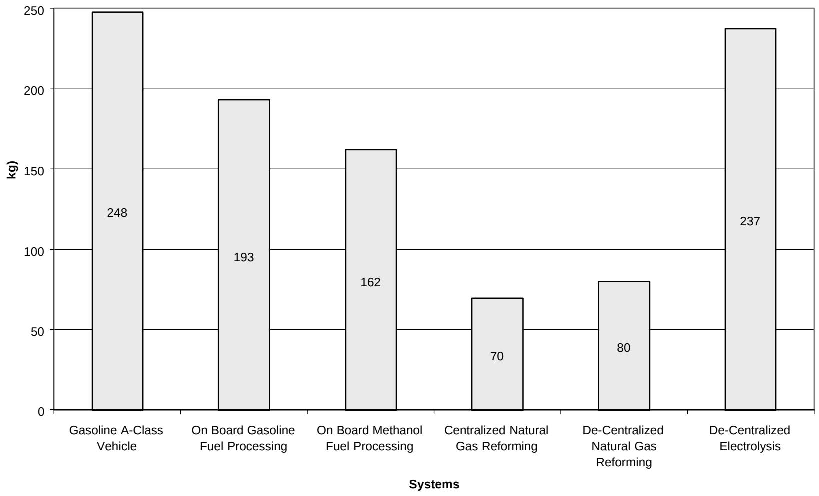
This assessment was done with a relatively small expenditure of time and resources compared with most full-fuel cycle life-cycle analysis studies and, in most cases, used best-available public domain data sets. While this will somewhat limit the precision of the results, the authors are nonetheless comfortable with the direction of the findings and the general conclusions (see Figure A).

When compared to the gasoline-powered baseline vehicle:

- The decentralized natural gas reforming system poses the fewest technical challenges and is expected to result in the most cost-effective hydrogen production system. This process has the potential to reduce life-cycle greenhouse gas emissions by up to 70 percent, compared with gasoline-powered conventional internal combustion engines.

- Decentralized electrolysis systems result in little reduction in greenhouse gases if the electricity is produced from a non-renewable resource, but can have significant reductions if the electricity grid is primarily hydro-electric.
- On-board fuel processing of gasoline or methanol results in a potential 20 to 30 percent reduction in greenhouse gas emissions.
- The decentralized natural gas reforming and electrolysis systems present the most feasible options with respect to infrastructure needs since they can be expanded incrementally as fuel cell vehicles increase in numbers. These options can also utilize existing natural gas and electrical grids, unlike the methanol option or centralized hydrogen production option.

Figure A. Total Greenhouse Gas Emissions for Each System (per 1000 km traveled)



The most important conclusions are that:

- The net greenhouse gas reduction benefits of the hydrogen fuel cell vehicle vary from minor to extremely significant, depending on which sources of hydrogen production are selected; and
- The net life-cycle implications of hydrogen fuel supply upstream of the vehicle must be considered in the further development of the fuel cell strategy. Otherwise a significant opportunity to reduce the impact of personal vehicles on climate change will be squandered.

This LCVA focused **only** on life-cycle greenhouse gas emissions, as the LCVA pertains to climate change and related policy matters. However, the preliminary work done here indicates that net life-cycle emissions of pollutants causing local air pollution and urban smog will also vary substantially with different choices in the hydrogen fuel supply systems. **Other areas that should be addressed** in conjunction with further work on the hydrogen fuel life cycle include:

- a quantitative comparison of the life-cycle emissions of ground level ozone precursors, hazardous air pollutants, acid deposition precursors, particulate matter, and other environmental wastes related to fuel processing and product manufacturing;
- an economic evaluation of the options using a model that incorporates social and environmental equity; and
- various sensitivity analyses on the factors considered in each LCVA scenario.

A life-cycle approach to system design improvements for the most climate-friendly systems could identify a number of means to further reduce environmental impacts from hydrogen-powered vehicle systems. Life-cycle assessment is essential to ensure that the future of the fuel cell leads to a genuinely more eco-efficient transportation system.

1 Introduction

The hydrogen fuel cell is an ideal power source to meet growing consumer demand for vehicles that have low tailpipe emissions, high fuel efficiency and immediate throttle response. Fuel cells were invented in the early 1800s, but the technology was not applied until the 1960s and ’70s when it was used on the Gemini and Apollo spacecraft. More recently, in response to increasing pressure to reduce emissions of smog precursors and emissions of greenhouse gases, major vehicle manufacturers have turned to the fuel cell as a potential alternative to the internal combustion engine.

Industries and governments all over the world have pointed to the fuel cell as the means to reduce greenhouse gas emissions from one of the single largest sources – personal vehicles. In theory, the only emissions from driving a hydrogen fuel cell-powered vehicle across the country would be a bathtub full of water. But, important questions to consider are: how is this hydrogen provided, and what emissions of greenhouse gases result from providing this hydrogen? This paper answers these questions by taking a life-cycle approach to evaluating the greenhouse gas emissions generated from traveling 1000 km in a hydrogen fuel cell-powered vehicle, using hydrogen produced from five different sources.

The underlying assumption of this work is that the development of fuel cell vehicle technology should follow the path that makes the greatest possible economic and environmental advancements. Environmental performance must be judged by assessing the entire life cycle of the technology. This approach clearly illustrates that the upstream processing technology used to generate a hydrogen fuel supply significantly affects the total greenhouse gas emissions produced by operating a hydrogen fuel cell-powered vehicle. A second strategic assumption is that it will be most effective to build on existing technologies and infrastructure, and to seek incremental changes in infrastructure rather than a massive overhaul.

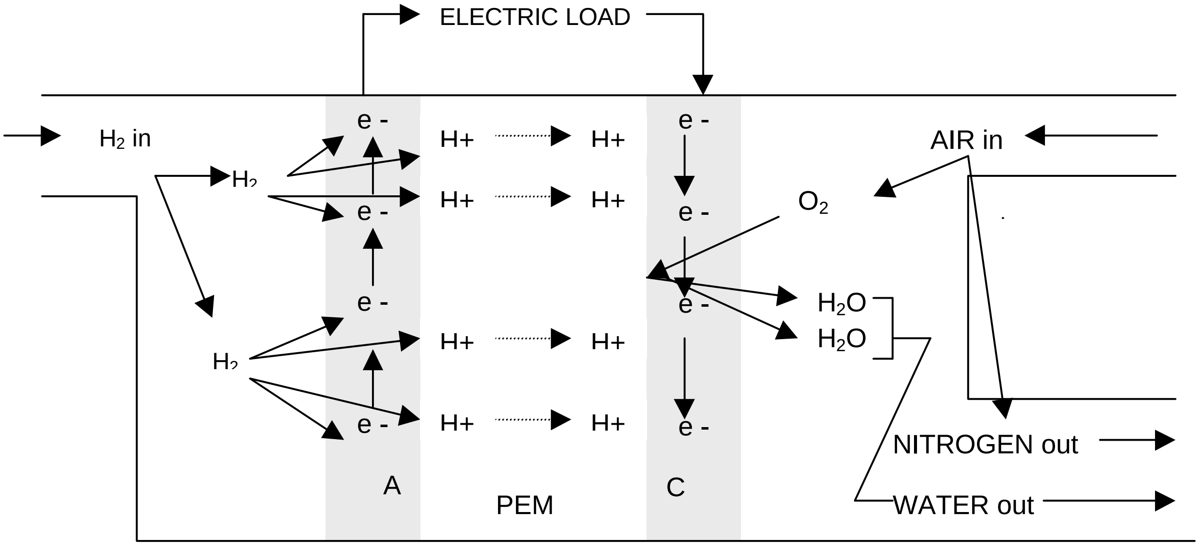
2 Background

2.1 What is a Fuel Cell?

A fuel cell converts energy stored in a fuel directly to electricity without combustion. Wet and dry cell batteries also use chemical reactions to produce electricity, but the supply of chemicals in a battery is finite. In a fuel cell, fuel can be fed continuously into the cell to produce electricity on an ongoing basis. With the right fuel, this is a highly efficient process resulting in no release of greenhouse gases. The fuel cell requires pure hydrogen or a hydrogen carrier such as methane (CH_4) that is converted to pure hydrogen using a hydrocarbon reformer.

A fuel cell consists of an anode, a cathode, and an electrolyte. In a typical fuel cell, hydrogen is introduced at the anode and splits into hydrogen ions and free electrons. The hydrogen ions flow through the electrolyte to the cathode where oxygen is introduced. At the cathode, the oxygen binds with the hydrogen ions to form water. To complete the process, the free electrons released at the anode must join with the hydrogen and oxygen at the cathode. The movement of electrons from anode to cathode creates a current that can be used to power an electric device.

Figure 2.1 Principles of the Hydrogen-Air Fuel Cell
(Kalhammer et al, 1998)



Anode Reaction: $2H_2 \rightarrow 4\,H^+ + 4\,e^-$
Cathode Reaction: $O_2 + 4\,H^+ + 4\,e^- \rightarrow 2\,H_2O$
Cell Reaction: $2\,H_2 + O_2 \rightarrow 2\,H_2O$ + electricity + heat

There are five kinds of fuel cells: phosphoric acid, solid polymer, molten carbonate, solid oxide, and alkaline. The system receiving most attention from the automotive sector is the solid polymer, or Proton Exchange Membrane (PEM), fuel cell. It has several advantages: a rapid start and shutdown time, safe and easy handling during manufacture and operation, and a solid electrolyte that simplifies the system and reduces cost (Dircks, 1999). PEM fuel cells can be arranged to deliver almost any combination of current and voltage.

Recent developments in technology make the fuel cell practical for automotive propulsion. Replacing conventional fossil fuel-powered vehicles with clean burning, fuel cell-powered vehicles (FCVs) could have substantial environmental benefits.

Fuel cells have two potential purposes: they could serve as a source of power for transportation, and as a small-scale power plant. A small-scale fuel cell could supply electricity to homes, offices and, conceivably, anywhere electricity is needed. However, to do so it needs a source of fuel, something that is often overlooked in popular discussions of the fuel cell's environmental potential.

2.2 Where Does the Fuel Come From?

The PEM fuel cell operates most efficiently on pure hydrogen (H_2). With pure hydrogen as the energy carrier ($2H_2O \rightarrow 2H_2 + O_2 \rightarrow 2H_2O$), the fuel cell's efficiency is unsurpassed and the system produces no pollution; that is, there are *no* tailpipe emissions of carbon dioxide, acid deposition precursors, smog forming precursors, or other combustion-related emissions. Furthermore, the driving performance of a hydrogen fuel cell-powered vehicle and a vehicle powered by an internal combustion engine are comparable (Mitchell, 1999). The challenge lies in providing a clean and sustainable supply of hydrogen to the vehicle. As Lovins and Williams (1999) state, "The key is not the fuel cell but rather how the fuel cell's best source of energy (hydrogen) will be manufactured, delivered, and stored."

There are three general strategies for producing, distributing and storing hydrogen.

1. Hydrogen can be produced by large centralized facilities and distributed via pipelines or trucks to refueling stations. This strategy is similar to the current refinery and gasoline station infrastructure.
2. Hydrogen can be produced at a larger number of smaller decentralized facilities. The hydrogen would be produced and delivered to the vehicle at the filling station, for example.
3. Fuel processors can be used to convert more traditional fuels, such as gasoline, methanol, ethanol and methane, into hydrogen directly on-board the vehicle. This option would make use of readily available fuels and existing infrastructure.

All options present their own technical challenges as well as environmental, economic, and societal costs and benefits. The aim of this paper is to use Life Cycle Value Assessment (LCVA) to investigate the comparative amounts of greenhouse gases produced from the entire fuel cycle inherent in each hydrogen generation and consumption option.

2.3 What is Life-Cycle Value Assessment (LCVA)?

LCVA is a technology evaluation and business decision-making tool that considers inputs and outputs related to the entire life cycle, from “cradle-to-grave,” of competing products or services. LCVA breaks down the life cycle of each option into a series of steps or unit processes and quantifies the environmental and economic performance for each process in each system. LCVA consists of five basic steps:

1. Goal Definition
2. Qualitative Scoping
3. Inventory Assessment
4. Impact Assessment
5. Improvement Assessment

LCVA was applied in this study with a focus on only one aspect of the environmental performance of fuel cell-powered vehicles–**emissions of greenhouse gases**. No “Improvement Assessment” was done to identify options for improving the performance of any of the fuel systems studied here. Further work is needed to complete a more in-depth study of other air emissions, water effluents, solid waste, and fuel and infrastructure costs throughout the life cycle of each option. Nevertheless, this study answers the very important question, “Which system of providing hydrogen to fuel cell vehicles should theoretically generate the least amount of greenhouse gas emissions?” To the authors’ knowledge, this is the first study of its kind using detailed data specific to Canada.

2.4 Study Objectives

The objective of this LCVA was to quantify the relative life-cycle emissions of greenhouse gases from various options available for producing hydrogen gas for automotive applications.

Specific questions to be answered by this LCVA were:

- What specific options or systems are available for providing hydrogen to fuel cell vehicles?
- What are the total life-cycle greenhouse gas emissions (that is, carbon dioxide, methane and nitrous oxide) for each system?
- Which choice of hydrogen production and distribution is most appropriate from a greenhouse gas perspective?
- Qualitatively, what other environmental, technical, financial, and social aspects must be considered for each option?

2.5 Identification and Selection of Systems to be Evaluated

The hydrogen production and distribution systems evaluated in this LCVA are listed in Table 2.1. The Mercedes-Benz A-Class vehicle, powered by a gasoline internal combustion engine, was used as the conventional technology baseline against which other options were compared. Different technology options were considered for each of the three general strategies of hydrogen production (centralized, decentralized and on-board).

Table 2.1 Hydrogen Production Systems Analyzed by this LCVA

	Name of System	Description of System	Reason(s) for Inclusion
A	Gasoline Internal Combustion Engine Vehicle (ICEV)	Gasoline is produced and delivered using conventional means. The Mercedes-Benz A-class ICEV is fueled with unleaded gasoline.	Considered in this report as the conventional technology baseline against which other technology options are compared.
B	On-Board Reformulated Gasoline Fuel Processing	Fuel cell vehicle with on-board fuel processor converting reformulated gasoline to hydrogen for direct use. No hydrogen storage on board.	Extensive research being completed in this area. Utilizes existing refueling infrastructure. (Refinery upgrading to reduce sulphur content may be required.) The gasoline reformer has been shown to successfully utilize cleaner California Phase II gasoline.
C	On-Board Methanol Fuel Processing	Fuel cell vehicle with on-board fuel processor converting methanol to hydrogen for direct use. No hydrogen storage on board.	Extensive research being completed in this area. Technology exists. Widely publicized as the “best” opportunity for the fuel cell.
D	Centralized Natural Gas (i.e., methane) Reforming	Produce hydrogen via large, steam methane reformers and distribute to filling stations using pipelines. Requires hydrogen storage at the filling station and on board the vehicle.	Proven technology for producing hydrogen. Considered to be the most potentially viable centralized option.
E	Decentralized Natural Gas (i.e., methane) Reforming	Hydrogen is produced at a number of smaller facilities, such as service stations, through methane reformers. Hydrogen is stored on board the vehicle.	Natural gas infrastructure exists. Technology for reforming exists.
F	Decentralized Electrolysis	Hydrogen is produced at a number of smaller facilities (located at home, business or service stations) through hydrolysis utilizing combined cycle natural gas electricity. Hydrogen is stored on board the vehicle.	Utilizes existing electricity infrastructure. Electrolysis technology exists.

A number of options for producing hydrogen were not evaluated in this study (see Table 2.2), including electrolysis using renewable or “green” sources of electricity. Although “green” electrolysis has the potential to result in the lowest emissions of greenhouse gases, the immediate supply of green power is limited and is assumed to replace other fossil fuel power before being used to produce hydrogen.

Table 2.2 Hydrogen Production Systems *not* Analyzed by this LCVA

Name of Fuel Cell System	Description of System	Reason for Exclusion
“Green Power” Electrolysis	Centralized or decentralized hydrogen production powered by photovoltaic, wind, and/or biomass power	Green power is not widely available. For large-scale application it is uncertain if green power will meet the necessary demand under present renewable electricity production capacities.
Bio-Methane Electrolysis	Centralized hydrogen production from methane collected from landfills, biomass, and livestock waste	Unlikely to produce large quantities of methane, therefore not expected to meet demand.
Biomass Feedstocks	Centralized hydrogen or methanol production from biomass feedstocks	Uncertain whether large quantities of product could be produced, therefore not expected to meet demand.
Nuclear Powered Electrolysis	Centralized hydrogen production using nuclear power	Due to its unacceptable environmental performance in key areas, nuclear power is not considered a sustainable option for producing hydrogen.
On-Board Ethanol Reformer	On-board fuel processor for ethanol	On a large scale and in the short term, ethanol supply is not expected to meet demand.
Centralized Electrolysis	Centralized hydrogen production at electricity plants and shipped to filling stations	If future growth in electricity demand is supplied by the combustion of natural gas, it would be inefficient to first use natural gas to produce electricity, then produce hydrogen, compared with producing hydrogen directly from the natural gas.

3 Method

Greenhouse gas emissions for each of the five hydrogen fuel cell powered-vehicle options were assessed and compared with a conventional internal combustion engine-powered vehicle of equal size and performance, using the Pembina Institute's LCVA modeling software. This section provides details on data sources, assumptions, portions of the life cycle considered in this study, and other scoping considerations.

3.1 Functional Unit

To produce a meaningful analysis and ensure that "apples are compared with apples," a common unit of comparison must be defined for each system or option. This end-use function of a process common to all systems being studied is called the "functional unit." Each system must be able to provide the service specified in the functional unit. The functional unit for this LCVA was defined as **1000 km traveled by the vehicle**. This distance assumes a pattern of 55 percent city driving and 45 percent highway driving in an A-Class Mercedes Benz (Figure 3.1). A driving range of 600 km per refueling is also assumed for each vehicle. The Mercedes A-Class was chosen for this study because it is the vehicle Ballard Automotive and Mercedes are developing for fuel cell market introduction. The conventional internal combustion model of the Mercedes A-Class has a fuel economy of 7.3 litres per 100 km. In comparison, the average fuel economy of a new vehicle on the road in Canada today is 9.2 litres per 100 km (Transportation Table, 1998).

Figure 3.1 Mercedes-Benz A-Class Vehicle

3.2 Process Flow Diagrams

A process flow map was developed to illustrate the life cycle system for each hydrogen gas production option. The process flow maps break down the cradle-to-grave life of the hydrogen production options for fuel cell vehicles into a sequence of "unit processes" or activities suitable for quantitative analysis.

Process flow maps are presented in section 3.6 (Figures 3.2 to 3.7) and accompany the unit process descriptions in Table 3.1. Life-cycle greenhouse gas emissions graphs appear in section 4 (Figures 4.1 to 4.6) and show the detailed breakdown of individual unit processes and corresponding greenhouse gas emissions.

3.3 Unit Process Scoping

The unit processes shown on the process flow maps were qualitatively investigated to identify inputs (e.g., materials, water, energy, or services) and outputs (e.g., pollutants, wastes, desirable services). Unit processes associated with manufacturing, maintaining, and decommissioning fuel cell vehicles were not included in the system process boundaries of investigation, as it was assumed that the relative differences among systems for these external processes would be minor.

3.4 Environmental Stressor Category Selection

Numerous feedstock materials and resources are required to deliver fuel via each of the hydrogen production options considered. Similarly, many waste outputs are generated. These are distributed over various processes, stages, locations and times within each system.

This LCVA directly addresses the quantitative greenhouse gas emissions produced from the fuel cycle of different fuel cell vehicle options. These gases are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The volumes are converted to CO_2-equivalent global warming potential values (CO_2 = 1.0, CH_4 = 21, N_2O = 310), as established by the Intergovernmental Panel on Climate Change based on a 100-year time horizon. Non-greenhouse gas emissions are considered qualitatively. Other stressor categories such as ground level ozone precursors, acid deposition precursors, particulate matter, hazardous air pollutants and water effluents should be evaluated quantitatively in a future analysis.

3.5 System Boundary Selection

The major life-cycle stages of the systems considered include:

- Raw Material Acquisition for the Fuel
- Fuel Processing and Refining
- Fuel Transport and Distribution
- Vehicle Operation.

These life-cycle activities represent the fuel cycle but do not represent the entire life cycle of fuel cell-powered vehicles. Although the manufacture of these vehicles was not considered in this analysis, the relative difference in emissions released in the production of each vehicle option is expected to be minimal.

3.6 Unit Process Descriptions

Unit processes, data sources, and assumptions are described in detail in the Appendix. The unit processes shown in the following process maps are documented in Table 3.1, which provides a summary of the data sources and key assumptions made in evaluating each fuel cycle.

Figure 3.2 System A: Gasoline Internal Combustion Engine Vehicle

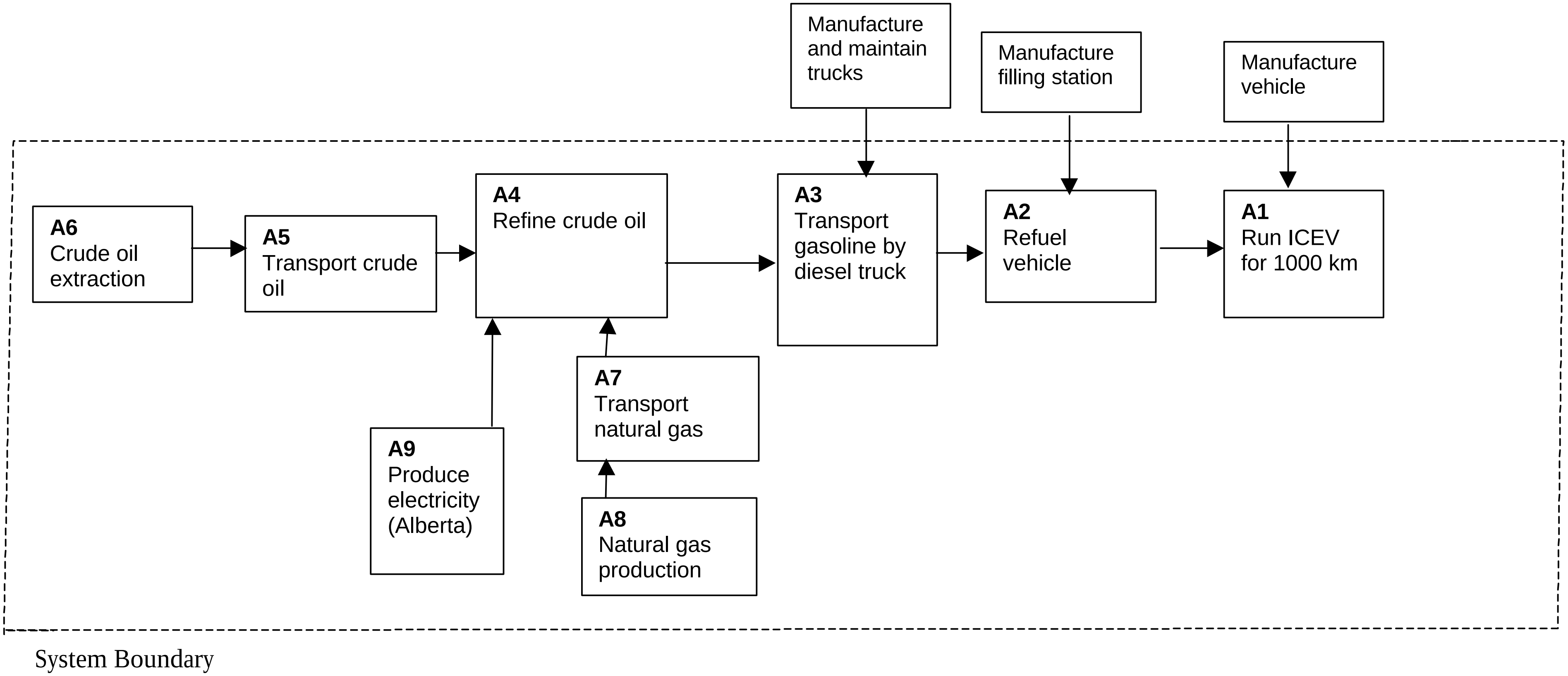


Figure 3.3 System B: On-Board Gasoline Fuel Processing

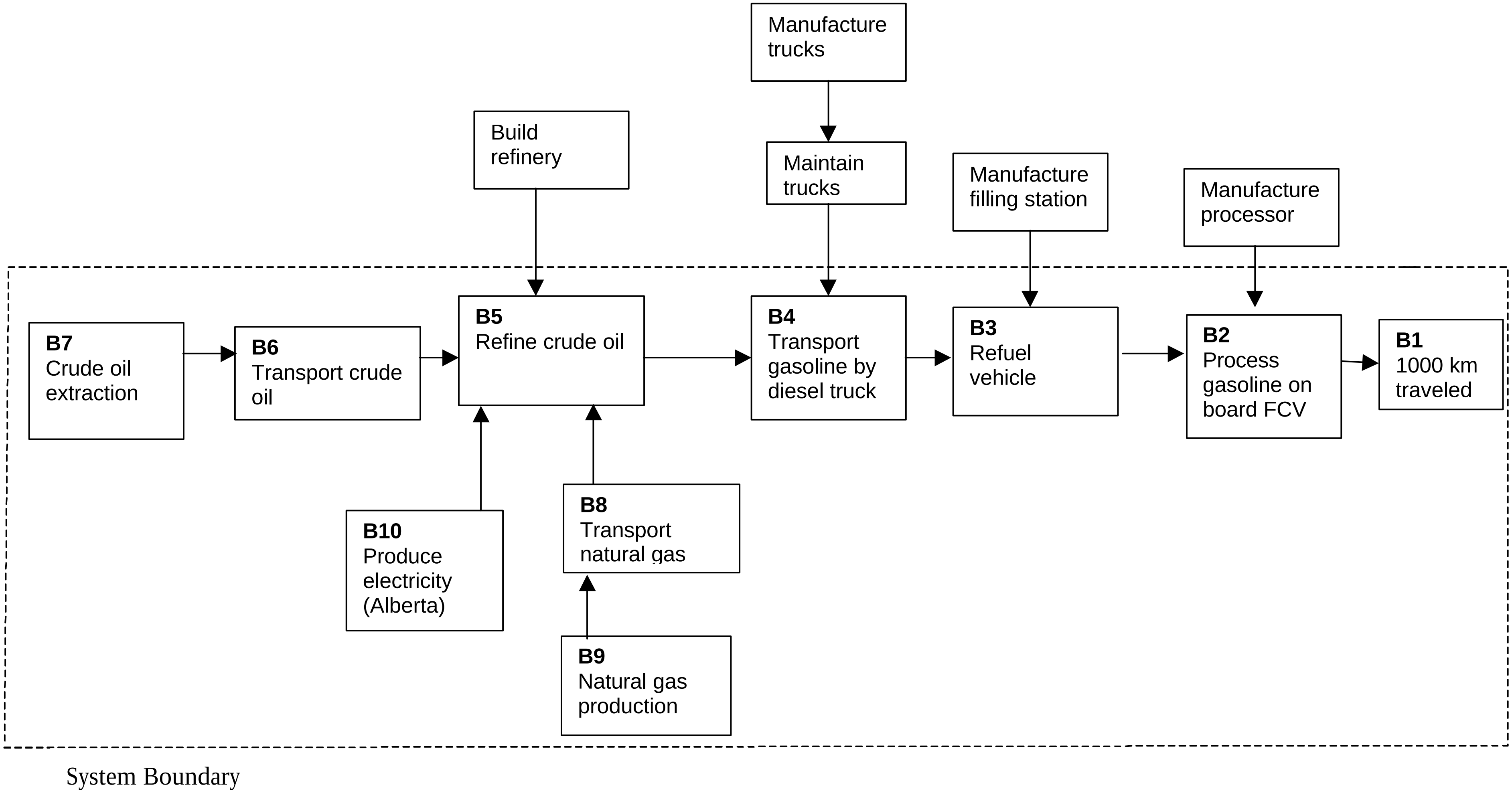


Figure 3.4 System C: On-Board Methanol Fuel Processing

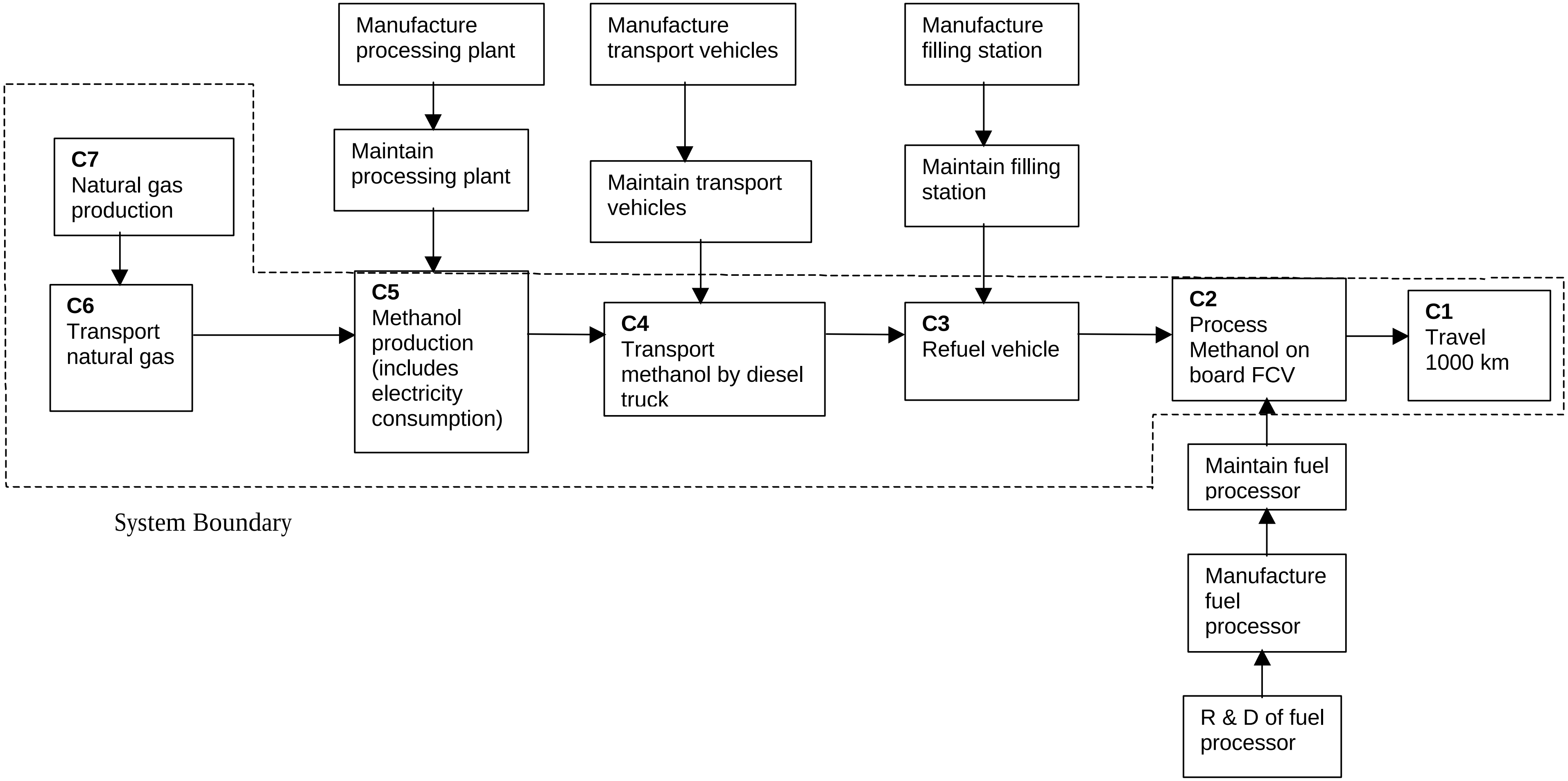


Figure 3.5 System D: Centralized Natural Gas Reforming

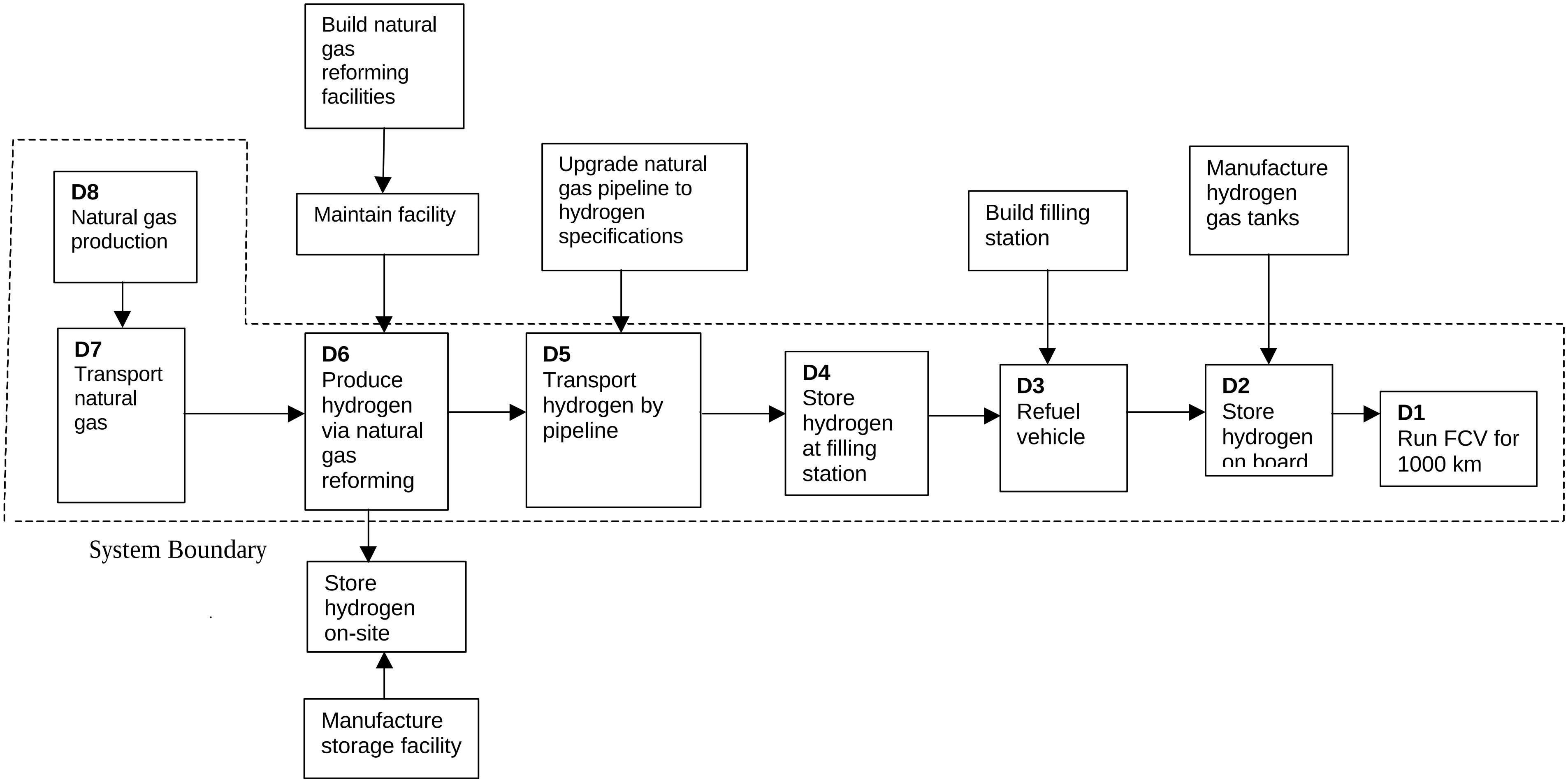


Figure 3. 6 System E: Decentralized Natural Gas Reforming

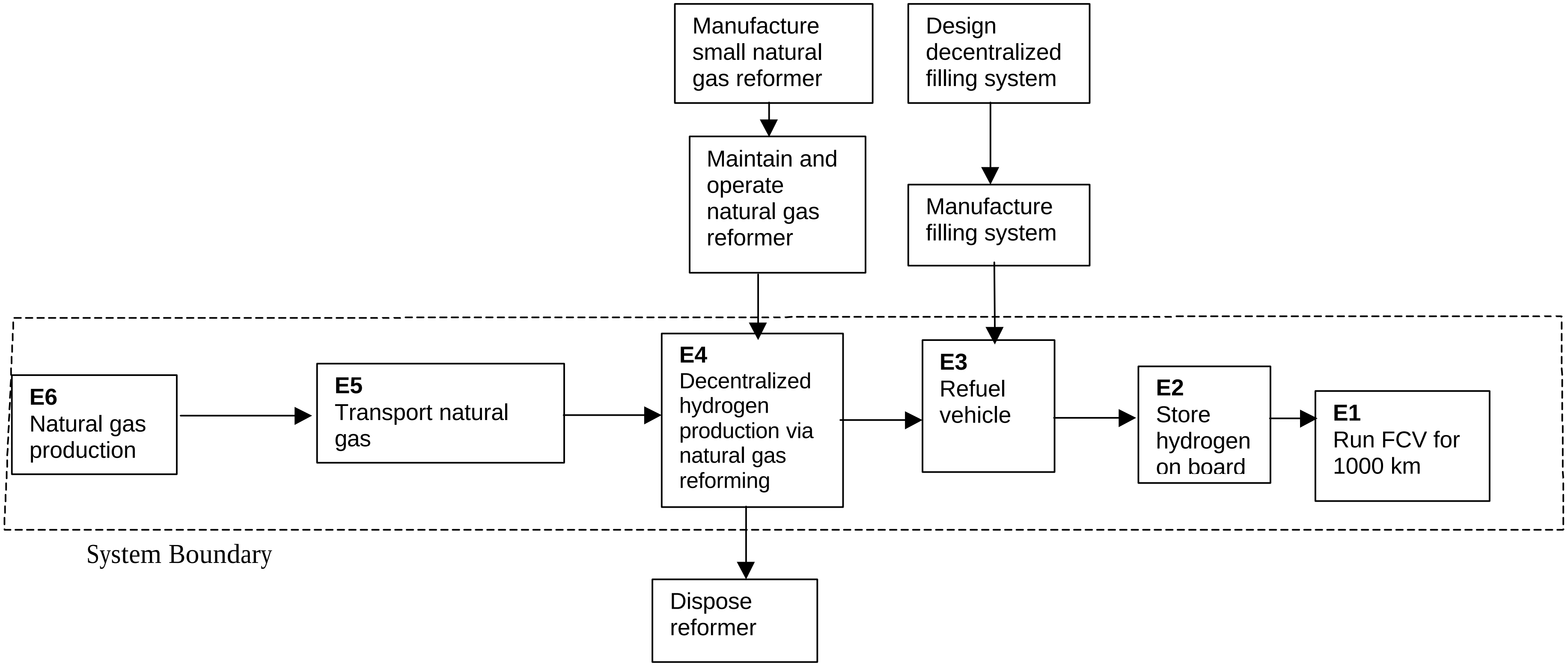


Figure 3. 7 System F: Decentralized Electrolysis

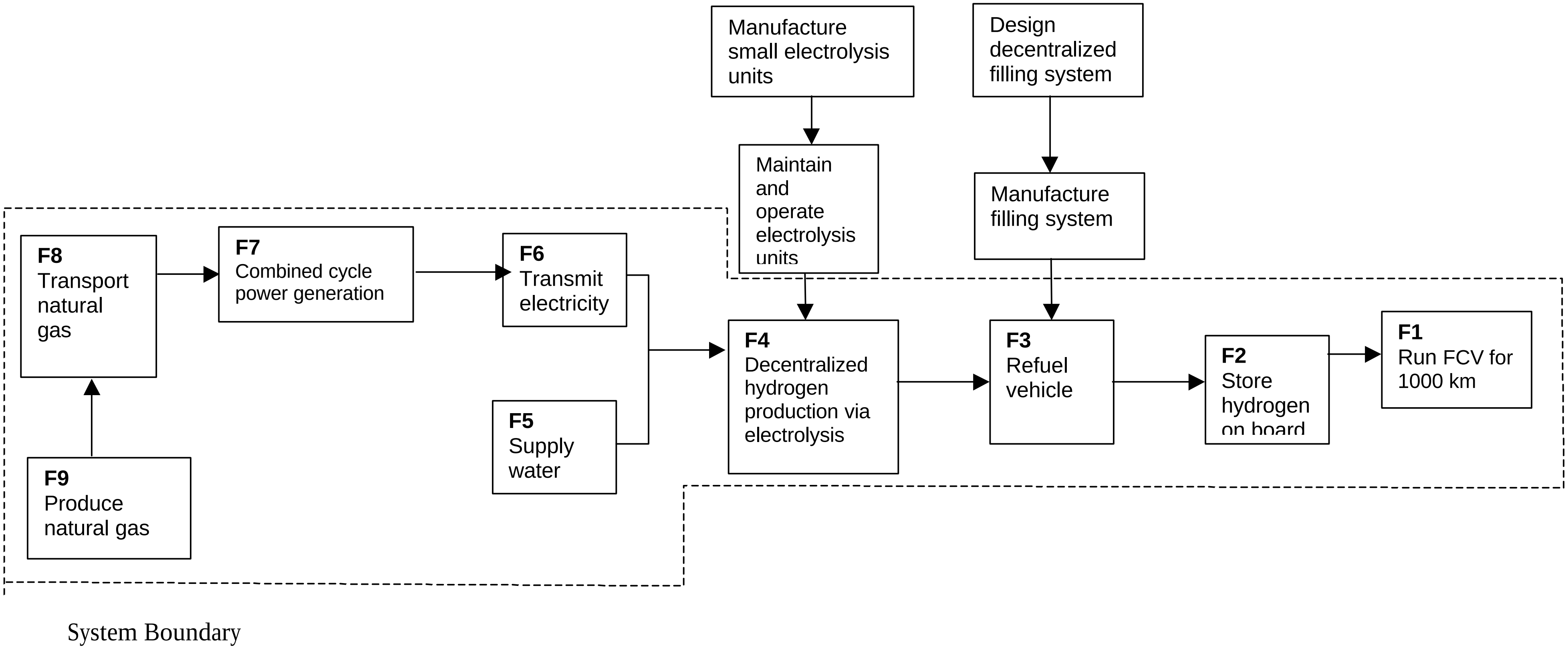


Table 3.1 Unit Process Summary

Unit Process	Brief Description	Data Source	Key Assumptions
B2 and C2 Process Gasoline or Methanol On-Board FCV	The multi-fuel "Next Millennium Fuel Processor"™ can be used to reform various feedstock fuels into hydrogen, which is then delivered to the fuel cell.	Ballard, 1999b; Mitchell et al, 1999; Ogden et al, 1997	- processor will use anode exhaust stream energy recovered from the PEM fuel cell - 38.5 miles per US gallon for the vehicle (70-75% efficiency for gasoline fuel processing) - 56.2 miles per US gallon gasoline equivalent (80-85% efficiency for methanol fuel processing) - efficiency based on Lower Heating Value (LHV) of H_2 to fuel cell divided by LHV of fuel into reformer - The methanol steam reformer is not considered here because of its slower response rate to hydrogen demand under normal driving conditions (Ogden et al, 1997) - Efficiencies used in this study are from recorded experimental reformer tests: California Phase II Gasoline – 83% Methanol – 88%
A2,B3,C3,D3, E3,F3 Refuel Vehicle	Pump fuel from storage facilities into vehicles at a local service station.	Levelton, 1999	-Emissions are from running pumps or compressors and evaporation or fugitive emissions from fuels and refueling systems.
A3, B4,C4 Transportation of Fuel by Diesel Truck	Gasoline and methanol will be transported by truck from a refinery or processing plant to local service stations.	Deluchi, 1991	-Emissions are from running diesel trucks. -Transport distance is 1000 km.
D5 Transportation of Hydrogen	Gaseous hydrogen is transported by pipeline to service stations. Truck transport of liquid hydrogen is not currently an industrial option being addressed though its costs have been demonstrated to be less than transport by pipeline.	NOVA Gas Transmission, 1997; Kalhammer et al, 1998; Ogden et al, 1997	- Proxy of greenhouse gas emissions from natural gas pipeline operation is used. - Hydrogen density = $23 kg/m^3$ @ 5000 psig. - Transport distance is 1000 km.
D1,E1,F1 Run Fuel Cell Vehicle for 1000 km	Hydrogen is introduced at the anode and splits into hydrogen ions and free electrons. Oxygen is introduced at the cathode and combines with hydrogen to form water. The movement of electrons from anode to cathode creates an electric current that is used to drive an electric motor.	Ballard, 1999b	- Hydrogen is produced externally and delivered to the vehicle at 300 ATM (or 34.5 MPa). - Regulators reduce the supply pressure of hydrogen from 34.5 MPa (storage pressure) to 3 ATM or 0.3 MPa (fuel cell operation pressure) - Direct hydrogen FCV attains 84.2 miles per US gallon gasoline-equivalent.

Unit Process	Brief Description	Data Source	Key Assumptions
D2,E2,F2 Store Hydrogen On-Board	Store compressed hydrogen on-board FCV in tanks. Space requirement concerns are addressed by inherent vehicle design.	Levelton, 1999; Ogden et al, 1997; James et al, 1997; Ballard, 1999b	- 4.7 kg of hydrogen will be stored on board to provide a 600 km range (380 miles).
D4 Store Hydrogen at Filling Station	Store compressed hydrogen in large containers that are designed to withstand embrittlement and release of fugitive emissions.	Levelton, 1999; Ogden et al, 1997; James et al, 1997	- Emissions result from producing electricity to run compressors and hydrogen lost due to fugitive emissions from compression process itself.
D6 Produce Hydrogen via Natural Gas Reforming	This process involves the catalytic conversion of methane and water at high temperatures (769-925°C) to produce carbon dioxide and hydrogen.	Mitchell et al, 1999; Birdsell and Willms, 1997; Levelton, 1999	- 83% efficiency (Lower Heating Value [LHV] of H_2 produced/LHV of fuel into reformer) - Emissions from plant construction, maintenance and operation were not considered.
A5,A7,B6,B8, C6,D7,E5,F8 Transport Natural Gas or Crude Oil via Pipeline	Natural gas is transported from the gas processing facility to a reforming plant to produce hydrogen.	NOVA Gas Transmission, 1997	- CO_2 emissions are from combustion in compressor engines, indirect electrical consumption, auxiliary fuel sources, and fugitive emissions. - transport 100 km to the central facility - density of methane = 0.7 kg/m^3
A8,B9,C7,D8, E6,F9 Natural Gas Production	This process includes the production of natural gas in the field and its processing within the plant. Emissions from electricity production are also included. The numbers from the field are aggregated. It is not clear what portion is flared or related to a particular process.	Monenco, 1994	- allocation by volume between propane and natural gas for gas production.
A4,B5 Refine Crude Oil	Crude oil is refined into gasoline	Monenco, 1994	- Same CO_2 emissions to refine California Phase II gasoline, which is assumed to be required for the on-board gasoline reformer system.
A6,B7 Crude Oil Extraction and Collection	Recovering oil from subterranean deposits and transporting it to the refinery.	Monenco, 1994	- Data represent Alberta average oil production.
C5 Methanol Production (Modern Steam Reforming Technology)	This process includes combining natural gas with water at high temperatures to produce methanol.	Borgwardt, 1998; Methanex, 1997; Methanex Memorandum, 29 Sept., 1999; Birdsell and Willms, 1997	- Emissions efficiency is based on information provided from Methanex indicating a range of CO_2 output, from that produced by the Kitimat plant in B.C. to modern day and future plant designs. - 0.38 tonne CO_2 eq/ tonne of methanol produced.

Unit Process	Brief Description	Data Source	Key Assumptions
E4 Decentralized Hydrogen Production via Natural Gas Reforming	Small scale "Multi-Fuel Processing" units will produce hydrogen to meet the needs of individual or family consumers at retail outlets.	Levelton, 1999	- Decentralized units are 10% less efficient than centralized plants due to potential economies of scale (based on analogy of central power plant efficiency at 33% and IC engine generator at 30%)
F4 Decentralized Hydrogen Production via Electrolysis	An electric current is passed through water to produce hydrogen and oxygen.	Levelton, 1999	- 68% efficiency (LHV hydrogen produced/MJ of electricity consumed) - 100% of water is converted to oxygen and hydrogen.
F5 Supply Water	Water requirements range from 3-9 kg H_2O/kg of H_2 produced.		- Water has to be either de-ionized or distilled.
A1 Run ICEV for 1000 km	The Mercedes-Benz A-class ICEV is used as a model for comparison. Reformulated gasoline is the fuel used.	Environment Canada, 1997; Mercedes-Benz	- Fuel efficiency is 7.3 litres/100 km (combined 45% highway, 55% city driving)
F7 Combined Cycle Power Generation	Steam turbine uses waste heat from natural gas fired turbine. Combined electricity generation increases efficiency of system.	Solar Turbines Inc., 1999.	- 46% efficiency (gas plus steam electricity/ LHV natural gas) - 60% efficiency could be claimed if the waste heat from the combined cycle were further utilized in a cogeneration configuration (e.g., power generation + district heating)
A9,B10 Produce Electricity	Represents the grid average emission profile for Alberta.	Monenco Agra, 1996	- This includes coal, natural gas and hydro power sources contributing 89%, 8%, and 3% respectively
F6 Transmit Electricity	Transmit electricity from power plant to desired location via conventional power lines		- A 7% line loss is assumed

4 Results

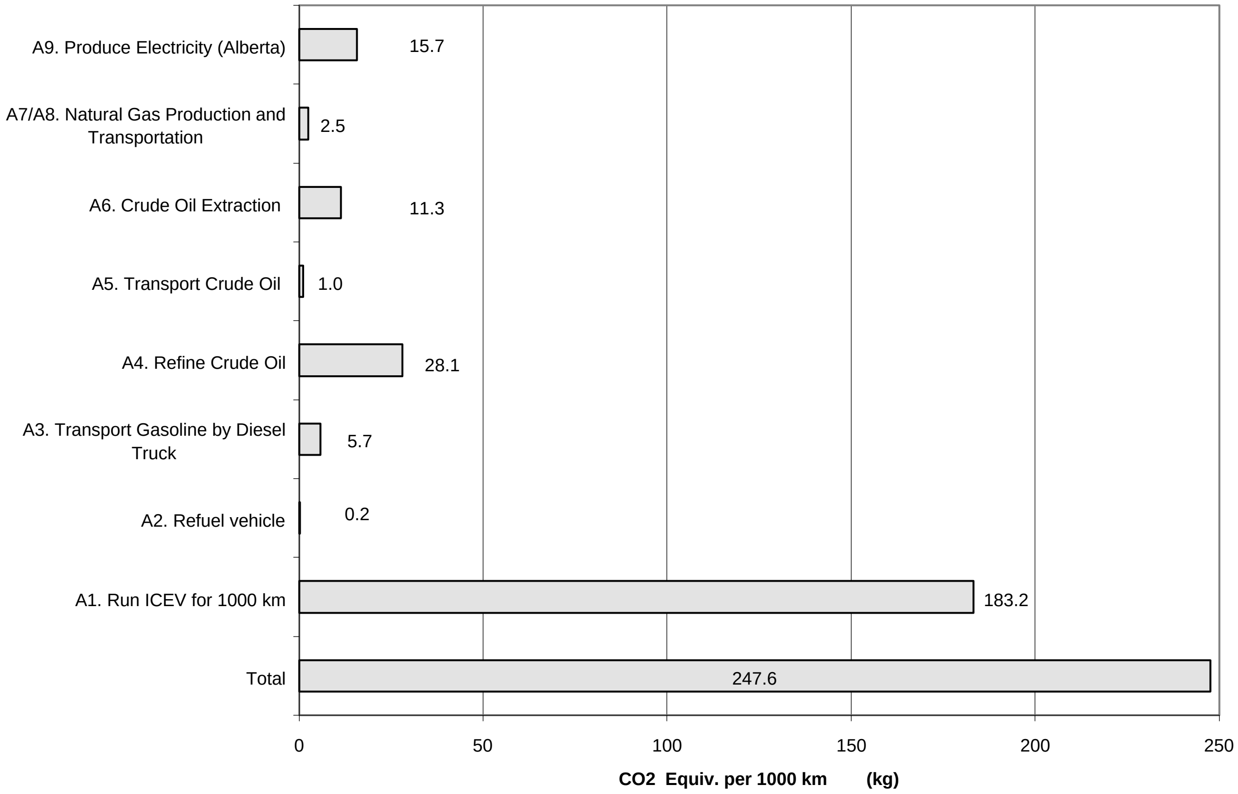
The CO_2 emissions throughout the life cycle of each system are presented in the series of figures below. Total CO_2-equivalents for each system are summarized in Section 4.7 (see Table 4.1 and Figure 4.7).

The results for each system are discussed and compared to a conventional Mercedes-Benz A-Class internal combustion-powered vehicle (System A). Manufactured by DaimlerChrysler, this vehicle is currently available in Europe and was used in this study to provide the baseline against which the emissions from the hydrogen fuel cell-powered vehicle options were compared.

4.1 System A: Gasoline A-Class Vehicle

The existing internal combustion engine vehicle (ICEV), the Mercedes-Benz A-class, emits just under 248 kg of CO_2-equivalents for every 1000 km of travel. Most of the emissions (74 percent) occur from the vehicle itself. Relatively few emissions occur upstream of this unit process, as illustrated in Figure 4.1.

Figure 4.1 Life-Cycle Greenhouse Gas Emissions from a Gasoline Vehicle over 1000 km of Travel



4.2 System B: On-Board Reformulated Gasoline Fuel Processor

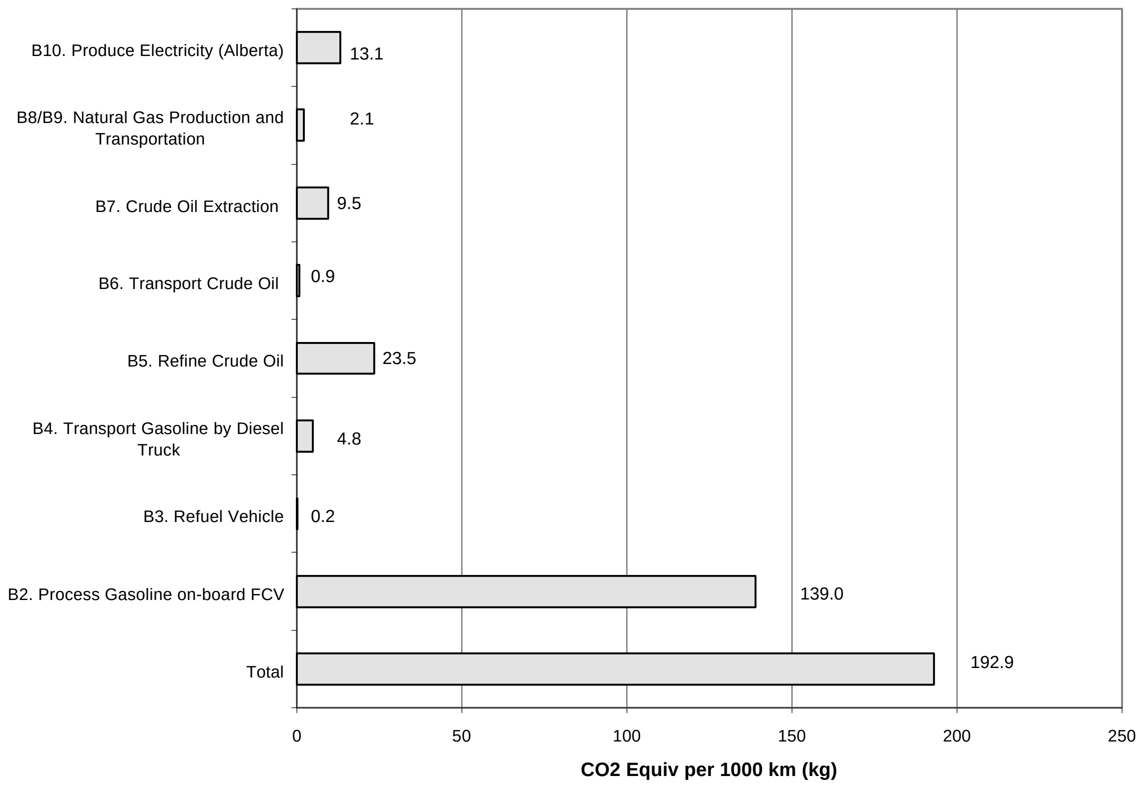
The reformulated gasoline powered-fuel cell vehicle is shown to produce approximately 22 percent less greenhouse gases than the conventional internal combustion Mercedes-Benz A-Class. While no greenhouse gases are emitted by the fuel cell itself, the hydrogen producer or “Multi-Fuel Processor” (MFP) is the major polluter, producing 72 percent of emissions. When gasoline combines with water at high temperatures, hydrogen and carbon dioxide are produced.

Because the atomic ratio of hydrogen to its carbon chain carrier (gasoline) is so low, the ratio of CO_2 to hydrogen produced from the reformer reaction is higher than what would be produced from a fuel with a higher hydrogen-to-carbon ratio. For example, methane (CH_4) would produce more hydrogen and less CO_2 than propane (C_3H_8) because CH_4 has a higher hydrogen-to-carbon ratio in its molecular structure.

Along with CO_2 emissions, the MFP emits carbon monoxide, hydrocarbons, and oxides of nitrogen. The MFP removes sulphur from the gasoline with the aid of a catalyst. The sulphur is stored on board and recycled at the end of the vehicle’s life.

Approximately 28 percent of the CO_2 emissions occur upstream of the vehicle. The largest upstream source is the refinery (12 percent of emissions), where reformulated gasoline is produced from crude oil. The results for each unit process are presented in Figure 4.2

Figure 4.2 Life-Cycle Greenhouse Gas Emissions from the On-Board Gasoline Reforming Fuel Cell over 1000 km of Travel

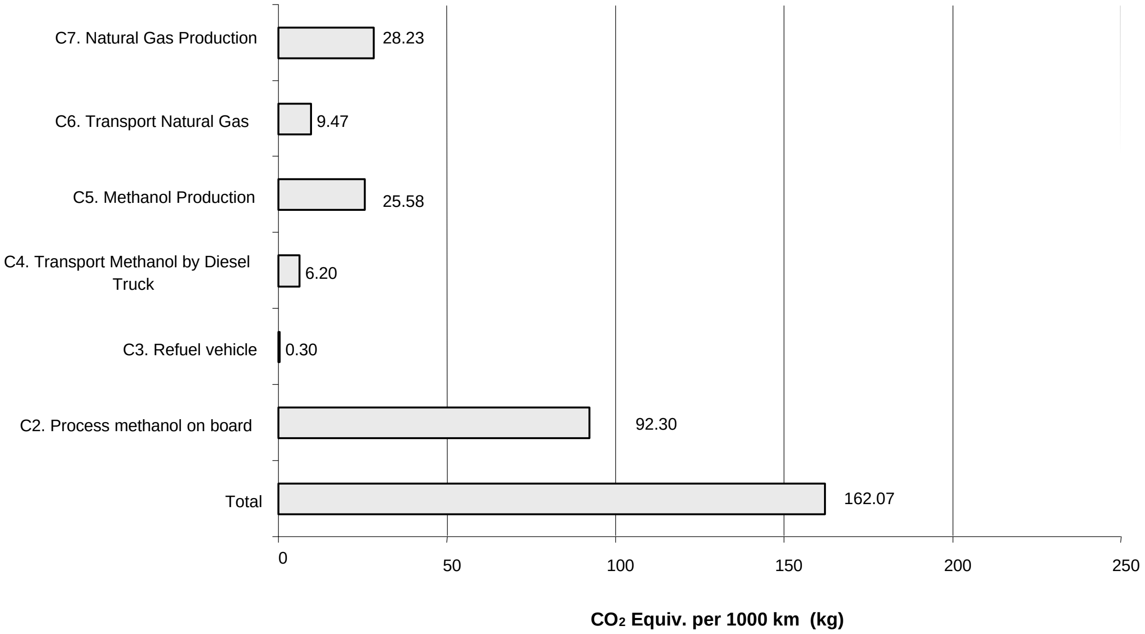


4.3 System C: On-Board Methanol Fuel Processor

Greenhouse gas emissions from the methanol fuel system are approximately 35 percent lower than those from the Mercedes-Benz ICEV. The methanol system results in 16 percent less emissions than the gasoline reforming system, providing notable greenhouse gas emission reductions over the gasoline fuel processor.

Similar to the on-board gasoline reforming system, most emissions (57 percent) for the methanol system occur on-board at the Multi-Fuel Processor. Significant emissions occur at the methanol production plant (16 percent), the natural gas wellhead (17 percent) and during natural gas transmission (6 percent). The extra steps required to produce methanol fuel reduce its overall environmental performance. Figure 4.3 shows the breakdown of emissions throughout the life cycle.

Figure 4.3 Life-Cycle Greenhouse Gas Emissions from the On-Board Methanol Reforming Fuel Cell over 1000 km of Travel

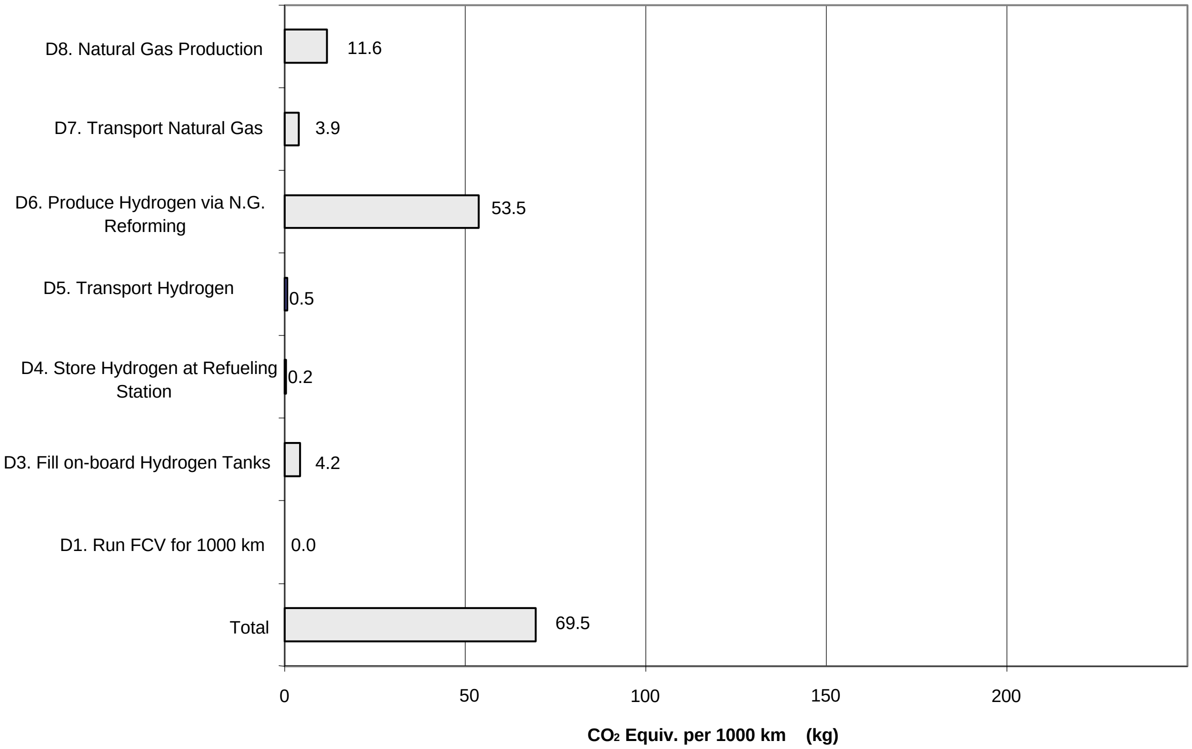


4.4 System D: Centralized Hydrogen Production via Natural Gas Reforming

The system with the lowest emissions of greenhouse gases is the on-board hydrogen storage fuel cell vehicle, with hydrogen produced in centralized natural gas reforming facilities. This system results in a reduction of greenhouse gases of nearly 72 percent over the ICEV. Most of these emissions (77 percent) occur at the large centralized natural gas reforming plants. In addition to natural gas inputs, the plant will require a source of fresh water. Natural gas steam reforming requires roughly 4.5 kilograms of water for every kilogram of hydrogen produced (Birdsell and Willms, 1997). This is approximately 25 litres of water per 1000 km of travel. Depending on the location of the facility, this water demand could be significant and should be considered when choosing a location for hydrogen production facilities.

Figure 4.4 clearly illustrates the low CO_2 outputs over the entire life cycle of the system. The relatively direct path from the natural gas wellhead, with minimal phase changes or chemical transformations en route to the fuel cell vehicle, results in the most efficient handling of the fuel supply of all the systems considered.

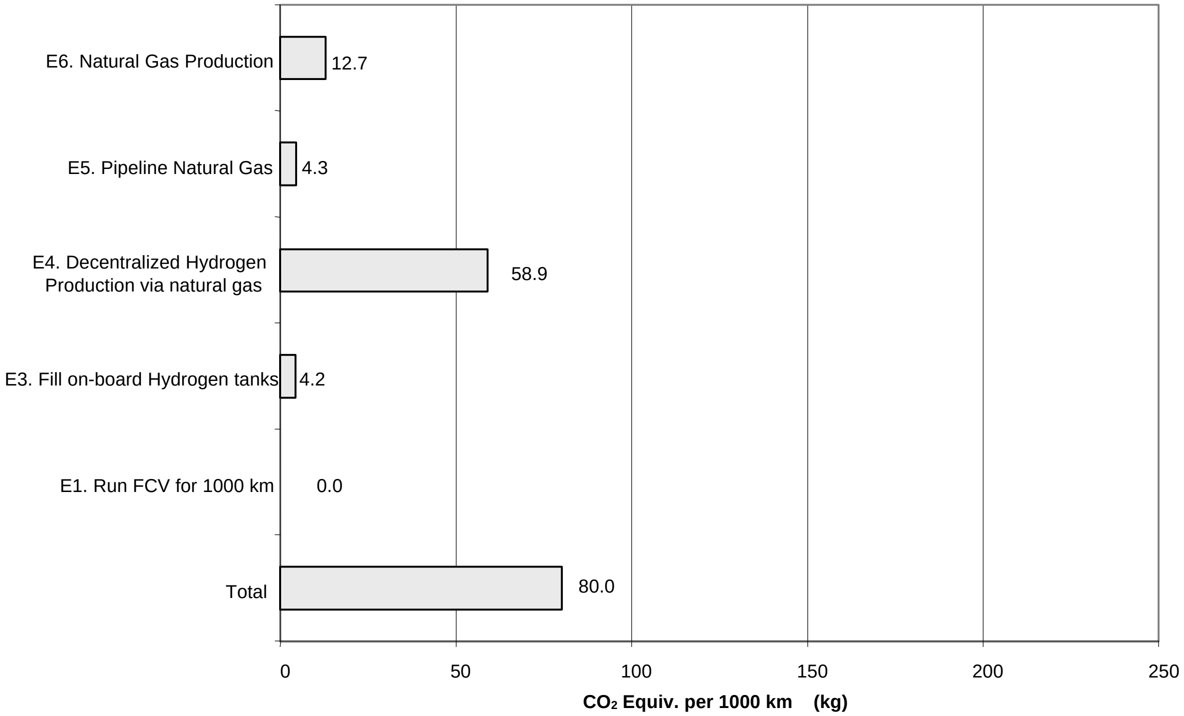
Figure 4.4 Life-Cycle Greenhouse Gas Emissions from the Centralized Hydrogen Production System Fueled by Natural Gas over 1000 km of Travel



4.5 System E: Decentralized Hydrogen Production via Natural Gas Reforming

Similar to the centralized system described in Section 4.4, the decentralized system produces about 68 percent less greenhouse gas emissions than the ICEV for every 1000 km traveled. The decentralized system results in around 15 percent more emissions than the centralized hydrogen production system, due in part to the assumption that decentralized hydrogen production would be 10 percent less efficient. Given the uncertainties in this technology, it is reasonable to assume that both the centralized and decentralized systems converting natural gas to hydrogen will result in approximately 70 percent less greenhouse gas emissions than the conventional internal combustion system. Figure 4.5 illustrates the carbon dioxide emissions throughout the life cycle. Most emissions (about 74 percent) occur at the facility where the natural gas steam reforming units are located. This process will require roughly 4.5 kilograms of water for every kilogram of hydrogen produced. (Birdsell and Willms, 1997). The water demand will not change according to location; rather, it will change with the size of the demand for hydrogen. This water demand could be an important consideration for municipalities investing in decentralized hydrogen production. The steam methane reformer "appliance" is expected to operate like many other home appliances, tapping into the existing residential natural gas supply and getting water directly from the tap.

Figure 4.5 Life-Cycle Greenhouse Gas Emissions from the Decentralized Hydrogen Production System Fueled by Natural Gas over 1000 km of Travel

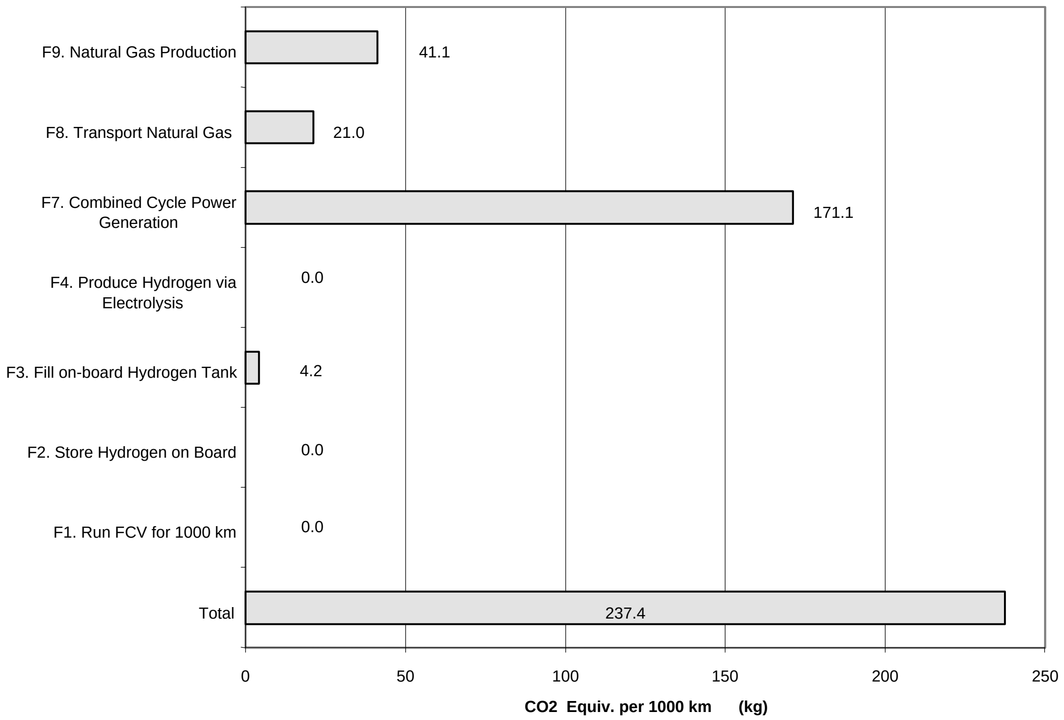


4.6 System F: Decentralized Electrolysis from Natural Gas Combined Cycle

The hydrogen production system with the most greenhouse gas emissions is the decentralized electrolysis system. Emissions from the system analyzed here are only five percent less than those from the gasoline internal combustion engine. Electrolysis itself produces no CO_2 emissions, but because electrolysis needs large quantities of electricity to separate hydrogen and oxygen from water, huge demands are placed on the electrical grid. This places higher demands on the fuels needed to power the electricity plants; in this case, a best-case natural gas fuel was assumed. Converting natural gas to electricity, then electricity to hydrogen, and finally hydrogen back to electricity for use in the vehicle is a very inefficient fuel production system and produces substantial amounts of greenhouse gases.

The distribution of greenhouse gas emissions for this system is illustrated in Figure 4.6. Seventy-two percent of greenhouse gas emissions comes from large centralized electricity plants that are assumed in this study to be high efficiency (46 percent) combined cycle natural gas-fired systems. Such a highly efficient power generation scheme is not the norm, but it illustrates that the greenhouse gas emissions generated by the electrolysis process – even when using the best fossil fuel electricity production system available today – represent a definite drawback for this option.

Figure 4.6 Life-Cycle Greenhouse Gas Emissions from the Decentralized Hydrogen Production System Utilizing Electrolysis over 1000 km of Travel



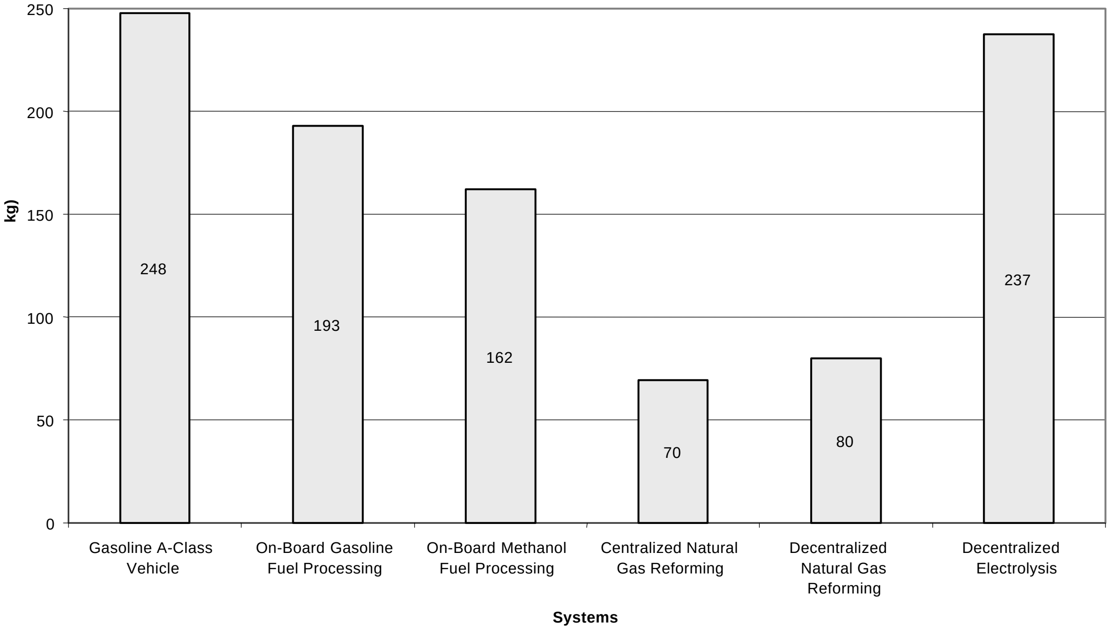
4.7 Comparison Summary

Carbon dioxide-equivalent emissions for all six systems are summarized in Table 4.1 and Figure 4.7. Of the fuel cell options, emissions are greatest for the decentralized electrolysis system. The lowest emissions are from the centralized natural gas steam reforming system. These numbers could also be presented in terms of annual emissions. The average annual CO_2-equivalent emissions for the decentralized electrolysis system are roughly 6,000 kg a year, based on the Canadian average of 25,000 km of travel annually. The least polluting system, centralized natural gas reforming, produces roughly 1,750 kg a year. If a price were assigned to carbon dioxide emissions, a potential three-fold saving would exist between these two extremes.

Table 4.1 Total Life-Cycle CO_2 Emissions for Each System over 1000 km of Travel and Annually (25,000 km)

System	CO_2-equiv. (kg / 1000 km of travel)	Annual CO_2-equiv. (kg / 25,000 km)
A. Gasoline A-Class Vehicle	248	6,200
B. On Board Gasoline Fuel Processing	193	4,800
C. On Board Methanol Fuel Processing	162	4,050
D. Centralized Natural Gas Reforming	70	1,750
E. Decentralized Natural Gas Reforming	80	2,000
F. Decentralized Electrolysis	237	6,000

Figure 4.7 Comparison of the Life-Cycle Greenhouse Gas Emissions for Each System, Assessed over 1000 km of Travel



5 Discussion

This section considers the greenhouse gas emission performance of each system analyzed, including a qualitative discussion on other environmental factors, technical barriers, and cost evaluation challenges. A strategy for public policy and industry is then developed, aimed at ensuring that the evolution of the fuel cell does in fact lead to a more eco-efficient transportation option.

5.1 On-Board Reformulated Gasoline and Methanol Fuel Processor

The LCVA results show a reduction of 20 to 30 percent in greenhouse gas emissions when operating a fuel cell vehicle with gasoline or methanol reforming on-board, compared with a conventional internal combustion engine-powered vehicle.

However, this improvement must be taken in the context of the study. The baseline gasoline-powered vehicle uses fuel at a rate of 7.3 litres/100 km. When considering aggregate emissions, it could be argued that the higher fuel efficiencies and lower greenhouse gas emissions of many of today’s smaller vehicles make them better performers than the internal combustion engine Mercedes. Many small vehicles today achieve fuel consumption levels of 5 litres/100 km and the emerging hybrid electric vehicles, such as the Toyota Prius, are capable of using less than 4 litres/100 km. Furthermore, a strong upcoming competitor to the hydrogen fuel cell could be Gasoline Direct Injection engines, which have the potential to improve internal combustion efficiency by at least 10 to 15 percent.

The greenhouse gas emissions of vehicles having higher fuel efficiencies and using hybrid technology were not compared on an aggregate basis to the Mercedes option. In addition, the development of other technologies, not mentioned in this study due to scope limitations, could also change the competitive stance of various options; for example, other unstudied options could achieve relatively greater greenhouse gas emission reductions than the on-board reformulated gasoline and methanol fuel processor options.

5.2 Centralized and Decentralized Hydrogen Production via Natural Gas Reforming

As this report clearly shows, reforming natural gas to produce hydrogen generates the lowest greenhouse gas emissions of the hydrogen fuel production options investigated. This result could be achieved through centralized or decentralized infrastructure, both of which reduce greenhouse gas emissions by approximately 70 percent from the baseline ICEV. The decision to invest in decentralized or centralized natural gas reforming is expected to be based more on technical and cost challenges than on greenhouse gas emissions.

The centralized natural gas system will result in non-greenhouse gas emissions upstream of the vehicle and typically outside the urban area. These systems may be located to shift urban air quality emissions outside the airshed of concern. The end result will be reduced smog precursors in the city, but increased emissions in industrial or rural areas. However, once the hydrogen is supplied to the vehicle, no gaseous tailpipe emissions are expected.

For the decentralized natural gas reforming option, non-greenhouse gas emissions will occur at the point of reforming (i.e., at the filling station), often in urban areas. Because the decentralized natural gas reforming systems will operate on high-grade methane and involve considerably larger units than on-board reforming systems using gasoline or methanol, it is reasonable to expect the natural gas system to result in lower overall exhaust emissions. On-board systems will be designed to be as compact and cost-effective as possible and may not have emission control systems that would be feasible on larger, stationary units. However, current data were not available to confirm this position.

5.3 Decentralized Electrolysis

Decentralized electrolysis was shown to be the least attractive option in this study, even when considering the use of rather highly efficient technology to produce the electricity required for the electrolysis process. If renewable resources were used to provide the power for the electrolysis process, the life-cycle emissions could be significantly reduced.

However, the current trend in new electricity generation capacity is towards increasing the use of natural gas, not renewable power. Thus it was assumed in this study that any additional renewable power put on the grid would offset conventional uses of electricity (e.g., residential, commercial, and industrial), and not be used specifically for producing hydrogen.

Hydrogen suppliers who adopt a strategy of expanding the capacity of renewable energy specifically to produce their hydrogen could change this situation.

5.4 Non-Greenhouse Gas Emissions Performance

Urban air quality is a major concern for an increasing number of cities in Canada and throughout the world. Gasoline and diesel vehicles are the main contributors to ground level ozone (smog), particulate matter, and other hazardous air pollutants in urban settings. Though these emissions should also be considered in choosing the type of fuel and supply system to reduce overall emissions, the inclusion of acid deposition precursors, ground level ozone generators, particulate matter, and other hazardous air pollutants is beyond the scope of this study. It is expected that in such a detailed analysis the natural gas reforming systems and electrolysis system (with a renewable energy-generated electricity supply) could result in the lowest emissions of non-greenhouse gases.

For the on-board fuel processing options (gasoline and methanol), emissions of volatile organic compounds (VOCs), nitrogen oxides (NOx), and carbon monoxide (CO) are generated from the vehicle's reformer. These emissions will likely occur in urban areas where most of the FCVs are expected to operate. Preliminary work has shown that the gasoline FCV may not meet the VOC emission standards set by the incoming Tier II, Ultra Low Emission Vehicle (ULEV), or Super Ultra Low Emission Vehicle (SULEV) guidelines for vehicles (Thomas et al, 1998). The methanol FCV meets all standards for NOx and CO, but does not meet SULEV guidelines for VOC emissions (see Table 5.1). Forecasts indicate this situation will be resolved. However, challenges still exist for on-board fuel processing systems to meet increasingly stringent vehicle emissions guidelines. Hydrogen FCVs are estimated to produce lower levels of emissions than the standards set for VOCs, CO and NOx (Thomas et al, 1998).

Table 5.1 Emissions Standards Not Now Met by Certain FCV Options

Standard	Gasoline FCV	Methanol FCV	Hydrogen FCV
Tier II – VOC	X		
ULEV – VOC	X		
SULEV – VOC	X	?[1]	
SULEV – CO			
SULEV – NOx			

In short, the natural gas reforming systems (Systems D and E) present the greatest potential for minimizing emissions of smog precursors, particulate matter, and other hazardous air pollutants. An electrolysis system operating on renewable power also has considerable potential to minimize these emissions. Current information is not available to quantify the relative performance of each option. Further analysis is required before governments and industry select a strategy for the future of the fuel cell vehicle to deal with emissions such as NOx and VOCs, as well as greenhouse gases.

5.5 Technology, Infrastructure and Cost Considerations

All five fuel cell options present challenges with respect to developments in technology and infrastructure, and in cost reduction. Each option has certain advantages and disadvantages. The costs of the fuel cell vehicle and storage systems need to be considered for all options. Table 5.2 compares the challenges for each of the five fuel cell systems.

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[1] This standard is 0.01 grams/mile. Information from Ballard Power Systems Inc. (Ballard Power Systems, 1999b) indicates the methanol FCV is expected to emit 0.0024 grams/mile (best case) and 0.0027 grams/mile (probable case), implying that the emissions would be much lower than the standard. Information from Directed Technologies Inc. (Thomas et al, 1998) indicates the methanol FCV is expected to emit 0.020 grams/mile (best case), and 0.023 grams/mile (probable case), implying the standard would be exceeded.

Table 5.2 Technology, Infrastructure and Cost Challenges of Each Fuel Cell System

System	Technical Challenges	Infrastructure Needs	Cost Considerations
B. **On Board Gasoline Fuel Processing**	- development of compact, lightweight, fuel efficient fuel processor	- some refiners will need to upgrade facilities to produce low sulphur gasoline	- cost of fuel processor - cost of producing low sulphur gasoline
C. **On-Board Methanol Fuel Processing**	- development of a compact, lightweight, fuel efficient fuel processor	- new infrastructure required to distribute methanol fuel	- cost of fuel processor - cost of methanol fuel infrastructure
D. **Centralized Natural Gas Reforming**	- development of cost effective means of transporting hydrogen over large distances - development of a vehicle and hydrogen storage system that provide acceptable performance and range	- new infrastructure required to distribute hydrogen	- cost of large scale hydrogen distribution infrastructure
E. **Decentralized Natural Gas Reforming**	- development of efficient, cost effective, medium sized natural gas reforming units - development of a vehicle and hydrogen storage system that provide acceptable performance and range	- could be minimal. (However, some distribution systems in urban areas are running tight on supply. An increase in load may require a utility to upgrade or consider operating its systems at higher pressures to accommodate new loads.) This option relies on the existing natural gas distribution system. Will require filling stations to install medium sized reformers. Expansion can occur on an incremental basis.	- cost of medium sized reformers - potential infrastructure upgrading costs related to the natural gas distribution system
F. **Decentralized Electrolysis**	- development of efficient, cost effective, medium sized electrolysis units - development of a vehicle and hydrogen storage system that provide acceptable performance and range	- very few. This option relies on the existing electrical grid, but will require filling stations to install medium sized electrolysis systems. Expansion can occur on an incremental basis.	- cost of electrolysis units - cost of electricity

5.5.1 Centralized vs. Decentralized Methane Reforming

An advantage of the decentralized natural gas reforming system over the centralized system is that the infrastructure can develop with the growth in the number of fuel cell-powered vehicles. This forestalls the need for an immediate capital infrastructure investment. Furthermore, decentralized hydrogen production presents the least technical challenge. The technology for hydrogen production from methane exists, the fuel cell vehicle technology exists, and the on-board storage system exists. The end result is that this option is presently the most technically feasible.

5.5.2 On-Board Reforming

The on-board fuel processing systems present significant technical challenges because of the complexity in converting gasoline and methanol to high-grade hydrogen in a compact, light, reliable, and efficient unit. It is also unknown how these systems will operate in Canada's cold climate. To reach operating conditions (i.e., the processor vaporizes methanol at about 150°C), it may be necessary to burn a large amount of fuel, producing greenhouse gases and other air emissions. Cold weather operation must be considered carefully when deciding which FCV system to pursue.

5.5.3 On-Board Methanol Reforming

The two common arguments for moving towards on-board methanol processing FCVs are:

1. on-board storage of hydrogen does not provide adequate vehicle range; and,
2. hydrogen will be too expensive compared with methanol (Kalhammer et al, 1998).

However, both of these arguments have been proven inaccurate.

Both Ford and DaimlerChrysler have demonstration vehicles that store enough compressed hydrogen on board with sufficient vehicle range and little loss in passenger and storage space (Thomas et al, 1998).

A detailed study by Thomas et al (1998) on the cost of different options for fuel cell vehicles showed the most cost-effective option to be the decentralized steam methane reforming unit with on-board storage of hydrogen. This work showed methanol to be the most expensive at a life-cycle cost 15 percent higher than conventional internal combustion vehicles. The methane reforming option was shown to result in a 30 percent cost savings per kilometre driven, compared with today's conventional vehicles. These results considered the entire life-cycle financial costs of vehicles, fuel, and infrastructure and were based on an urban area supporting more than 10,000 fuel cell-powered vehicles.

5.6 Discussion Limitations

A full discussion of all pertinent facts and factors in comparing hydrogen production options for FCVs requires a study of much greater scope than that undertaken here. Three areas of note were not specifically addressed in this study and these limitations should be addressed in subsequent studies:

1. This study only recognized greenhouse gases and their equivalents, ignoring all other forms of waste generated from the life cycle options investigated.
2. The economics did not address full cost accounting concerns that include environmental and social as well as economic impacts.
3. Individual LCVA component sensitivities were not assessed (e.g., determining the effect on the greenhouse gas emissions profile of using higher or lower efficiency reformers).

6 Conclusions

Although one of the most effective means of reducing emissions from transportation is to reduce our reliance on personal vehicles, achieving significant emission reductions from vehicles is essential. This study indicates that the FCV has the potential to improve on existing gasoline technology and deliver substantially lower levels of greenhouse gas emissions on a life-cycle basis, **if** the most climate-friendly hydrogen sources are used. However, different systems vary considerably in their life-cycle greenhouse gas emissions benefits. The LCVA results show significant differences in the life-cycle emissions from five different fuel cell options.

6.1 Non-Greenhouse Gas Emissions

- Natural gas reforming systems (Systems D and E) present the greatest potential for minimizing emissions of smog precursors, particulate matter, and other hazardous air pollutants. An electrolysis system operating on renewable green power also has considerable potential for minimizing these emissions but, with the limited resources available, this study did not attempt to quantify the relative performance of each option for local air pollution impacts.

6.2 Greenhouse Gas Emissions

- Steam methane reforming of natural gas to produce hydrogen for on-board storage results in the greatest potential to reduce life-cycle greenhouse gas emissions. These systems, either centralized or decentralized, could reduce emissions by approximately 70 percent.

- Decentralized electrolysis systems result in little reduction in greenhouse gases if the electricity is produced from a non-renewable resource.

- On-board fuel processing of gasoline or methanol yields a 20 to 30 percent reduction in greenhouse gas emissions compared with the conventional internal combustion vehicle.

- The decentralized natural gas reforming system appears, in the short term, to pose the fewest technical challenges and is expected to result in the most cost-effective hydrogen production system. The decentralized natural gas and electrolysis systems present the most feasible options with respect to infrastructure needs since they can be expanded incrementally as fuel cell vehicles increase in numbers. These options can also use existing natural gas and electrical distribution networks, unlike the methanol option or centralized hydrogen production option.

7 Recommendations

The fundamental objective of this investigation was to bring attention to the fact that the upstream processing option chosen to produce hydrogen fuel directly affects the life-cycle greenhouse gas emissions profile for the hydrogen fuel cell-powered vehicle. Further, within the scope and level of detail provided, this paper determines and recommends strategies to minimize greenhouse emissions in the FCV life cycle. It is clear that some options could lead to FCVs having a large advantage over existing gasoline combustion technology. The proposed recommendations originate from this perspective.

7.1 Corporate Strategy and Public Policy Considerations for the Future Deployment of Fuel Cell Vehicles

This section includes a short discussion on the policy implications of this LCVA. It looks at the strategic issues related to developing the fuel infrastructure for FCVs, and how decisions on this infrastructure will affect the comparative greenhouse gas advantage of FCVs. These comments are directed towards public policy makers in the Canadian and British Columbia governments, corporate strategists and investors in the Ballard / DaimlerChrysler / Ford alliance and other fuel cell manufacturers, and potential fuel providers.

7.1.1 Maintaining the Life-Cycle Environmental Advantage

The automobile industry’s interest in the fuel cell arose primarily because of environmental concerns and the need to meet scheduled and anticipated car emission standards. The fuel cell is now considered the preferred low-emission replacement for the internal combustion engine. The environmental image of the fuel cell is built on the message that FCVs have trace or zero gaseous emissions; this is true, but only at the tailpipe.

The life-cycle perspective is increasingly affecting both public policy and private sector procurement, particularly in Europe, and in light of international commitments to address climate change. In the market of the future, it may not be enough to have the lowest tailpipe emissions. The FCV should be assessed on the basis of its life-cycle emissions – from the production of its hydrogen fuel through to the tailpipe.

Emissions from FCVs typically have been compared with emissions from the conventional internal combustion engine, as in this study. However, the fuel cell engine is only one of several initiatives underway by the auto industry to develop a “green” car. Other efforts include electric, hybrid electric, and direct injection engine development. Thus future competition for the FCV will come as much from these other advanced-power green cars as from conventional cars.

To maintain its position as the environmentally preferred fuel system, the FCV must therefore remain ecologically competitive, on a life-cycle basis, with other “green” cars. But as shown by the analysis in this study, the life-cycle greenhouse gas advantage of the FCV over an ICEV ranges from 10 percent to 70 percent, depending on the options pursued to supply the hydrogen fuel. In contrast, gasoline direct injection can improve the fuel efficiency of conventional gasoline vehicles by 10 to 15 percent (Levelton, 1999). Hybrid electric vehicles with a 45 percent improvement in fuel efficiency are already on the market; the Toyota Prius, for example, uses 4 litres/100 km, compared with the Mercedes Benz A-class at 7.3 litres/100 km. Gasoline fuel efficiency can be used as a rough indicator of likely greenhouse gas emissions. Thus the greenhouse gas advantage of FCVs compared with conventional high efficiency competitors will only be maintained with certain hydrogen supply options: natural gas reforming or electrolysis using renewable power sources.

7.1.2 Implications for Ballard/DaimlerChrysler/Ford Alliances with Fuel Suppliers

No consensus currently exists on which fuel option should be used for FCVs. However, the leading option being developed by the Ballard/DaimlerChrysler/Ford alliance is on-board methanol fuel processing. In June 1999, Ballard Power Systems signed a memorandum of understanding with Petro-Canada and Methanex to establish a commercially viable fuel distribution network to meet the expected market demand for fuel cell vehicles, starting with a methanol fuel source (Ballard et al, 1999). Unfortunately, on-board processing of methanol fuel does not offer anything near to the life-cycle greenhouse gas advantage of natural gas reforming.

The information provided in this study should encourage the Ballard/Petro-Canada/Methanex associates to investigate infrastructure requirements for hydrogen derived from natural gas reforming, and also to consider design improvements that will reduce the greenhouse gas intensity of hydrogen derived from methanol fuels.

This information should also encourage natural gas companies to investigate the potential market opportunities for natural gas reforming that could arise from the commercialized use of FCVs, and to examine how FCVs could affect their core business.

Hydrogen producers and fuel cell and FCV manufacturers should consider developing alliances with the renewable electricity industry, natural gas utilities, and companies that can assist in the development of high pressure delivery and on-board storage technology to coordinate the development of a complete hydrogen fuel system infrastructure.

Ultimately, renewable power could be used to produce hydrogen in decentralized electrolysis appliances; this option has the potential to produce ultra-low greenhouse gas emissions throughout the fuel cycle of the fuel cell-powered vehicle.

7.1.3 Implications for Public Policy

Canada has a strong strategic interest in seeing the PEM fuel cell emerge as a leading substitute for the internal combustion engine. We must significantly reduce air emissions to alleviate global, regional, and local environmental and health problems. Economically, the success of the PEM fuel cell could bring tremendous regional economic benefits to Western Canada.

Public and government demand for an ultra-low or zero emissions vehicle has fostered FCV development. This study demonstrates that an ill-informed choice of fuel and technology for the FCV could lead to only modest emission reductions on a life-cycle basis–an unfortunate squandering when informed decisions could lead to impressive emission reductions. This underscores the need to maintain a life-cycle perspective in all environmental policy and new technology developments.

Responsibility for encouraging a market for low emissions vehicle systems can also be partially assigned to government. The role governments take in policy development can greatly improve the acceptance rate of the low emissions FCV in the marketplace. Government actions should include:

- providing incentives to generate an interest in using small vehicles that operate on hydrogen;
- sponsoring a demonstration project of a small fleet of vehicles with on-board hydrogen storage coming from either a decentralized natural gas reforming system or electrolysis from green power system; and
- supporting the development of medium-sized steam methane reformers for service stations and other potential applications.

7.2 Further Research

Further studies need to be completed to compare vehicle options and clearly define the status of various eco-efficient transportation options and the fuel of choice. Such studies should include environmental outputs beyond just greenhouse gases, and should consider regional differences and related infrastructure costs for Canada, all with appropriate sensitivity analyses.

In addition, a quantitative comparison of the life-cycle emissions of ground level ozone precursors, hazardous air pollutants, acid deposition precursors, and particulate matter needs to be undertaken and assessed in terms of a full cost accounting methodology, before considerable funds are invested to develop fuel production and distribution systems.

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Appendix: Description of Data Sources and Assumptions

Process Gasoline and Methanol On Board Fuel Cell Vehicle

Description:

To solve the hydrogen supply problem, a multi-fuel processor (MFP) was developed. As the name suggests, the MFP will reform California Phase II gasoline, methanol, ethanol, or natural gas into hydrogen. Hydrogen is then delivered to the PEM fuel cell. The MFP includes six main steps:

1. Fuel is vaporized using waste energy from fuel cell.
2. Vaporized fuel is burned with a small amount of air in POX (partial oxidation) reactor to produce CO and H_2.
3. Sulphur is removed.
4. Steam is reacted with most CO to form additional hydrogen and CO_2.
5. Remaining CO is preferentially oxidized (burnt) over a catalyst to reduce emissions to less than 10 ppm.
6. The hydrogen gas combines with air in the fuel cell to form electricity, water and heat to propel vehicle.

Essentially, the MFP and PEM fuel cell combined with an electric motor would replace the internal combustion engine (ICE). This engine's performance is expected to be comparable to conventional ICE motors.

Data Source:

Information on the Epyx Corp. "Multi-Fuel Processor" is found on the Epyx website (www.epyx.com) and in the paper written by William Mitchell et al. (1999). Ballard Power Systems provided fuel efficiencies.

Assumptions:

The MFP will be used in conjunction with a PEM fuel cell and will operate on heat recovered from the fuel cell. Data are based on steady state operation (i.e., little transient response was achievable during lab testing). The efficiencies are 83% for gasoline and 88% for methanol (Lower Heating Value [LHV] of H_2 produced/LHV of fuel into reformer). The performance of the MFP will be similar to the ICE with respect to acceleration, reliability, maintenance, safety and driver satisfaction. Although currently not in commercial production, it is expected the MFP must meet these criteria prior to commercialization.

Fill Vehicle

Description:

This process is similar to current vehicle refueling procedures; that is, pumping fuel from storage facilities into vehicles at a local service station. Gasoline will necessitate little or no upgrading to service stations and fuel supply infrastructures. Methanol will require special fuel lines and storage components to guard against its extremely corrosive properties. Hydrogen refueling procedures will be similar to compressed natural gas refueling. However, substantial upgrading to valves and adapters will be needed to contain the extremely small hydrogen molecules. All metal pipes and storage containers need to be treated to prevent hydrogen embrittlement.

Data Source:

Data calculated from information found in "Alternative and future fuels and energy sources for road vehicles." This report was prepared for the Transportation Issue Table, National Climate Change Process and delivered by Levelton Engineering LTD and S & T Consulting Inc.

Assumptions:

Emissions are from running pumps or compressors and from the vaporization and evaporation of fuels.

Transport Commodity by Truck

Description:

Methanol and gasoline are transported from the refinery or methanol plant to local service stations by tank truck. For the centralized hydrogen production system, it is assumed the hydrogen is transported to fueling stations by truck.

Data Source:

"Emission of Greenhouse Gases from the use of Transportation Fuels and Electricity," Volume 2, Appendix A, U.S. Department of Energy, M. Deluchi (1991).

Assumptions:

Emissions are from running diesel truck engines and emissions volumes depend on the grade of diesel, type and age of truck, and traveling speed (A traveling distance of 100 km is assumed for this LCVA).

Run Fuel Cell Vehicle (FCV)

Description:

A fuel cell consists of an anode, a cathode and an electrolyte. In a PEM fuel cell hydrogen is introduced at the anode and splits into hydrogen ions and free electrons. The hydrogen ions flow through the electrolyte to the cathode where oxygen is introduced. At the cathode the oxygen binds with the hydrogen ions to form water. In order for the process to be complete the free electrons, released at the anode, must join with the hydrogen and oxygen at the cathode. The movement of electrons from anode to cathode creates an electric current that can be used to power an electric device. An A-Class Mercedes Benz hydrogen FCV operating on compressed hydrogen is expected to obtain 84.2 miles per gallon gasoline equivalent (mpgge). The "probable case" reported by Ballard for the methanol and gasoline on-board fuel processing systems are 56.2 mpgge and 38.5 mpgge respectively. Each vehicle is designed to have a 600 km driving range on a tank of fuel.

Data Sources:

Preliminary reading and data recovery included a number of papers listed in the Bibliography. Data concerning efficiency were provided by K. Washington of Ballard Power Systems on July 5, 1999. The information is based on Environmental Protection Agency combined highway and urban driving cycles of FCV fuel economy estimates for a Mercedes-Benz A-class vehicle.

Assumptions:

This unit process assumes hydrogen is produced externally and delivered directly to the fuel cell at 3 ATM in an A-class Mercedes Benz vehicle. Pressure regulators control the supply of hydrogen from 34.5 MPa (storage pressure) to 0.3 MPa (fuel cell operation pressure).

Store Hydrogen On Board

Description:

This unit process involves storing hydrogen on board vehicles in tanks similar to, but bulkier than regular gasoline tanks. Compressed hydrogen tanks offer rapid refueling capacity, little fugitive emissions, minimal infrastructure costs, high safety due to the inherent strength of the pressure vessel, and simplicity of design. Ambient temperature compressed gas storage (as opposed to liquefied hydrogen storage) is considered the most appropriate fuel storage system.

Data Source:

Information sources include Levelton (1999) and James et al (1997).

Assumptions:

For a 600 km range, 4.7 kg of hydrogen will be required (Ballard).

Store Hydrogen at Filling Station

Description:

The storage facility must guard against embrittlement and fugitive emissions. Storing hydrogen at a service station will require a large compressor to achieve the desirable 300 ATM delivery and storage pressure.

Data Source:

Levelton, 1999.

Assumptions:

Emissions result from producing electricity to operate compressors.

Produce Hydrogen via Natural Gas Reforming

Description:

Steam methane reforming at large centralized facilities is currently the most widely used, cost effective and efficient hydrogen production process. The process involves the catalytic conversion of methane and water at high temperatures (769-925° C) to produce carbon dioxide and hydrogen (Levelton, 1999). A large-scale methane reforming plant can achieve fuel conversion efficiencies of 83 percent (LHV of H_2 produced/LHV of fuel into reformer) (Mitchell, 1999). The chemical process that occurs is:

$$CH_4 + H_2O \Leftrightarrow CO + 3H_2 \qquad (1)$$

$$CO + H_2O \Leftrightarrow CO_2 + H_2 \qquad (2)$$

This combined chemical reaction suggests that a large amount of carbon dioxide is produced per unit hydrogen (ratio is roughly 5.5 kg CO_2 :1 kg H_2). The produced hydrogen is delivered via truck to appropriate filling stations for use in FCVs. If centralized hydrogen production were to expand to supply a large fleet of vehicles it would be feasible to consider transporting the hydrogen through pipelines. This evaluation assumes the hydrogen supplies to be transported by truck.

Data Source:

Data set calculated from information found in “Alternative and future fuels and energy sources for road vehicles.” This report was prepared for the Transportation Issue Table, National Climate Change Process and delivered by Levelton Engineering LTD and S & T Consulting Inc. Other papers consulted include Mitchell et al (1999) and Birdsell and Willms (1997).

Assumptions:

Emissions from plant construction, maintenance and operation were not considered.

Transport Natural Gas and Crude Oil via Pipeline

Description:

Natural gas and crude oil will be pipelined from processing facilities to reforming plants.

Data Source:

NOVA Gas Transmission of NOVA Chemicals Inc. Voluntary Climate Change Challenge and Registry report for 1996.

Assumptions:

It is assumed that for CO_2, 93 percent of these emissions are from combustion at compressor engine stations, with five percent being from indirect electrical consumption at transmission facilities, and two percent from auxiliary fuel sources, vented gas, and vehicle emissions. Fugitive emissions of methane are also included.

Natural Gas Production

Description:

This process includes the production of natural gas in the field and its processing within the plant.

Data Source:

The data are a summation of the results of the Full Fuel Cycle study performed by Monenco in 1992 and the Monenco-AGRA study performed in 1996 for TransAlta Utilities.

Assumptions:

Field production methods will vary. No distinction is made between sweet gas and sour gas processing. The data set used in this LCVA assumes allocation by volume between propane and natural gas for gas production. Data assume 80 percent of raw gas becomes processed to sales gas, with the remaining 20 percent as flared gas, acid gas and by-products (ethane, propane, etc.). Gas processing is assumed to have an 84 percent recovery rate. Data include indirect emissions from electricity production.

Refine Crude Oil

Description:

Crude oil along with small quantities of synthetic crude are refined into gasoline.

Data Source:

Petro-Canada Products Inc., Petro-Canada Edmonton Oil Refinery Application for License Renewal, 1993. Alberta Environmental Protection and Enhancement Act application: 002-10184.

Assumptions:

The end products do not include California Phase II gasoline, however, this LCVA assumes refinery emissions are the same. Assume no changes in the refinery operations have occurred since 1993 (as no more recent applications for renewal have been submitted).

Crude Oil Extraction and Pipeline

Description:

These two unit processes include recovering oil from subterranean deposits and shipping it via pipeline to the refinery.

Data Source:

Information on crude oil extraction at the well and transport to the refinery is based on the 1992 Monenco data set.

Methanol Production

Description:

The most readily available source of methanol is from natural gas. This process includes combining natural gas and water at high temperatures to form methanol. Conventional steam reforming can yield 0.782 mole of methanol from 1 mole of natural gas. A combination of natural gas and biomass as a feedstock for methanol production may be more effective.

Data Source:

Papers cited include Borgwardt (1998) and Birdsell and Willms (1997). Supplemented with data obtained from contact at Methanex:, Michael McDonald. The information is representative of typical methanol operations.

Assumptions:

Numbers are based on information provided by the Kitimat plant in B.C.

Decentralized Hydrogen Production via Natural Gas Reforming

Description:

Home, office building, or service station units will produce hydrogen to meet the needs of individual consumers. For example, a home unit might produce enough hydrogen to fill an FCV tank on a daily or weekly basis. Home reformers will use the existing natural gas infrastructure to supply the feedstock.

Data Source:

Data set calculated from information found in “Alternative and future fuels and energy sources for road vehicles.” This report was prepared for the Transportation Issue Table, National Climate Change Process and delivered by Levelton Engineering LTD and S & T Consulting Inc.

Assumptions:

Smaller units will not be as efficient as large plants (assume 10 percent less than centralized plant).

Decentralized Hydrogen Production via Electrolysis

Description:

An electric current is passed through water to produce hydrogen and oxygen. Small, decentralized units (i.e., home or office) are used to produce sufficient hydrogen for personal use. Initially, these units would provide the most flexibility at the lowest capital cost for early market entry.

Data Source:

Data set calculated from information found in “Alternative and future fuels and energy sources for road vehicles.” This report was prepared for the Transportation Issue Table, National Climate Change Process and delivered by Levelton Engineering LTD and S & T Consulting Inc.

Assumptions:

It is assumed that 100 percent of water is converted to hydrogen and oxygen.

Supply Water

Description:

Most hydrogen production options require significant amounts of de-ionized or distilled water. Hydrogen production systems require three to nine units of water for every unit of hydrogen produced. The ramifications of extremely large water consumption should be considered during any decision-making process.

Assumptions:

This LCVA assumes there will be a readily available source of fresh water.

Run ICEV for 1000 km

Description:

The Mercedes-Benz A-class ICEV is used as a model for comparison. Reformulated gasoline is the fuel used. The A-class vehicle is among the most efficient ICEVs on the market today and is a likely candidate for the fuel cell.

Data Source:

Combustion information from Environment Canada, 1997. Vehicle efficiency verbally obtained from a Mercedes-Benz Dealer.

Assumptions:

Fuel efficiency is 7.3 litres/100 km for combined 45 percent highway, 55 percent city driving.

Combined Cycle Power Generation

Description:

Combined cycle power generation is considered to be one of the most efficient systems for producing power from natural gas. The system involves a gas turbine to produce power followed by a heat-recovery-steam-generator to produce steam from the turbine exhaust. This steam is utilized in a steam turbine to produce additional power.

Data Source:

Efficiency determined by verbal communication with Pete Hovde of Solar Turbines Inc. Located in San Diego, California; tel: (619) 694-6215.

Assumptions:

First-law thermodynamic efficiency of the plant is 46 percent. Assumed 100 percent of fuel is converted to carbon dioxide. Efficiencies of up to 60 percent can be realized if the waste heat is utilized in an external process, such as district heating.

Produce Electricity (Alberta)

Description:

Represents the average emissions from the Alberta grid.

Data Source:

These data were supplied by TransAlta, based on information obtained through a study performed by Monenco Agra Inc. in 1996.

Assumptions:

This includes coal, natural gas and hydro power sources contributing 89 percent, 8 percent, and 3 percent respectively.

Transmit Electricity

Description:

Transmit electricity from power plant to desired location via conventional power lines.

Assumptions:

There are no greenhouse gases emitted during electricity transmission but a 7 percent line loss (average Alberta grid) is assumed.