Life-Cycle Value Assessment (LCVA) of Fuel Supply Options for Fuel Cell Vehicles in Canada

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Disclaimer

This Life-Cycle Value Assessment is based on the extent of data available to the project team at the time of data collection. Consequently, the project team was required to compromise in order to compare technologies at different maturity levels and vehicles of different body type and performance. Every effort has been made to maintain consistency between the systems compared, and, where this was not possible, the inconsistencies have been clearly identified throughout the report.

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LIST OF ABBREVIATIONS

AB	Alberta
ADP	Acid Deposition Precursor
B.C. or BC	British Columbia
CAN	Canada
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EC	Environment Canada
FC	Fuel Cell
EPA	Environmental Protection Agency (U.S.)
EV	Electric Vehicle
FCV	Fuel Cell Vehicle
GHG	Greenhouse Gas
GLOP	Ground-level Ozone Precursor
HEV	Hybrid Electric Vehicle
HLW	High Level Waste
IC	Internal Combustion
ICE	Internal Combustion Engine
MFCV	Fuel cell vehicle with on-board methanol processing
MPG	Miles per Gallon
MPGGE	Miles per Equivalent Gallon of Gasoline
NO_X	Nitrogen Oxides
ON	Ontario
LCVA	Life-Cycle Value Assessment
LDV	Light-Duty Vehicle
LLW	Low Level Waste
PPM	Parts Per Million
PM	Particulate Matter
SAE	Society of Automotive Engineers
SCR	Selective Catalytic Reduction
SO_X	Sulphur Oxides
SO_2	Sulphur Dioxide
SPM	Suspended Particulate Matter
SPMP	Secondary Particulate Matter Precursor
TSP	Total Suspended Particulate
U.S.	United States
VOC	Volatile Organic Compounds

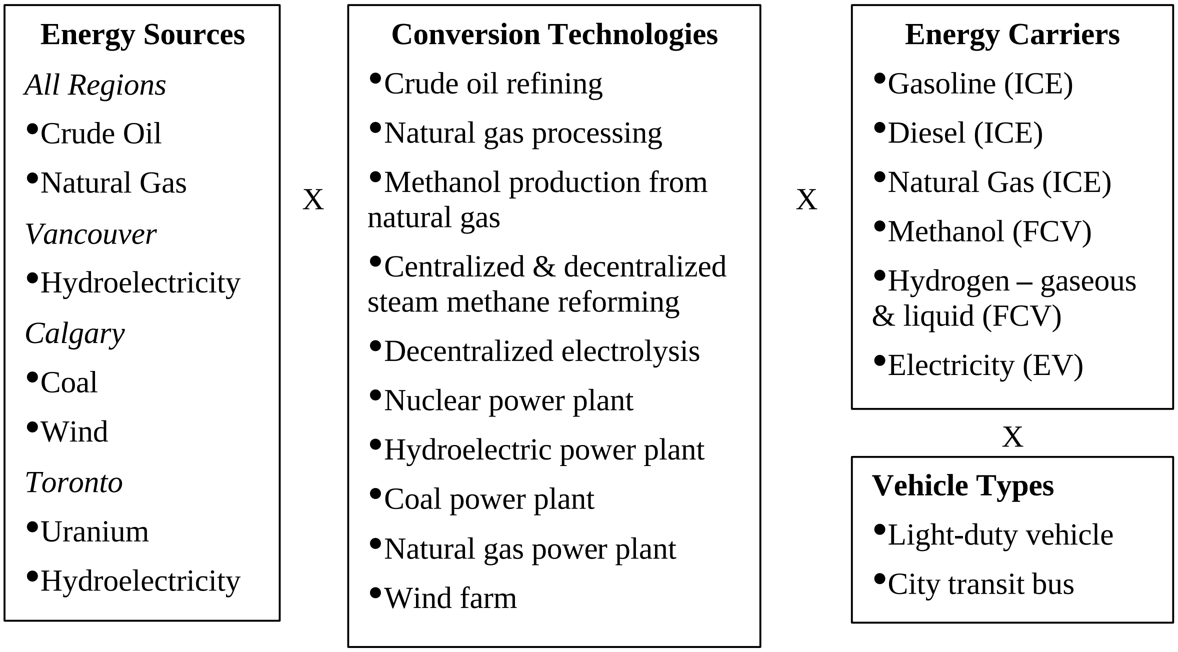
Executive Summary

The fuel cell vehicle (FCV) could revolutionize the world's transportation systems. With the potential for near-zero tailpipe emissions, greater vehicle performance, increased fuel efficiency and lack of dependence on crude oil compared to conventional internal combustion engines (ICEs), FCVs could effect a dramatic improvement in urban air quality, climate change, overall energy consumption and energy security. However, as choices are made about sources of fuel for FCVs, it is important to consider the life-cycle performance of each option or fuel supply system, since for many fuel choices the majority of emissions occur before the fuel reaches the FCV.

The objective of this Life-Cycle Value Assessment (LCVA) is to quantify and evaluate the life-cycle environmental and economic factors of a wide range of technically advanced (i.e., poised for commercialization with actual performance data available) options for operating light-duty vehicles and buses in Canada. In addition, this LCVA qualitatively identifies technical design challenges and improvement opportunities, along with social costs and benefits. Since some of these technologies have not yet fully matured, the relative performances of the various technologies, and consequently the conclusions being drawn about them, are expected to change in the future. The performances of not-yet-commercialized technologies are believed to have the greatest potential to improve, given their relatively low level of maturity.

This LCVA looks specifically at three Canadian cities – Toronto, Vancouver and Calgary – and at both light-duty vehicles and buses. Figure ES.1 illustrates the system components. A number of other potential technologies were initially considered, but were eliminated from this study owing to limited available data. In total, 72 different scenarios (unique city, vehicle and fuelling pathway combinations) are evaluated in this study.

Figure ES.1 Energy and Technology Types Selected for Assessment



Energy Sources

All Regions
- Crude Oil
- Natural Gas

Vancouver
- Hydroelectricity

Calgary
- Coal
- Wind

Toronto
- Uranium
- Hydroelectricity

X

Conversion Technologies
- Crude oil refining
- Natural gas processing
- Methanol production from natural gas
- Centralized & decentralized steam methane reforming
- Decentralized electrolysis
- Nuclear power plant
- Hydroelectric power plant
- Coal power plant
- Natural gas power plant
- Wind farm

X

Energy Carriers
- Gasoline (ICE)
- Diesel (ICE)
- Natural Gas (ICE)
- Methanol (FCV)
- Hydrogen – gaseous & liquid (FCV)
- Electricity (EV)

X

Vehicle Types
- Light-duty vehicle
- City transit bus

Overall Conclusions

Conclusions drawn from this LCVA include:

- Fuel cell vehicles fuelled with hydrogen from renewable energy-based electrolysis show the greatest opportunity for minimizing negative environmental and social impacts of vehicle / fuel supply systems. However, at the current level of technology maturity, fuel costs are estimated to be higher for electrolysis-based systems than for conventional vehicles.
- Where renewable energy is not available, steam methane reforming (SMR) technology is the next most environmentally benign source of hydrogen, although distribution logistics for centralized plants and the operational issues of decentralized plants remain as hurdles. SMR-based FCV systems are also estimated to have fuel costs comparable to fuel costs for gasoline light-duty vehicles, but higher than diesel bus fuel costs at the current level of technology maturity.
- Liquid hydrogen requires a considerable increase in electricity compared with gaseous hydrogen, due to compression, which adversely affects overall life-cycle environmental performance and fuel cost.
- Natural gas–based electrolysis for hydrogen FCVs has both advantages and disadvantages when considering their life-cycle air emissions. For most of the natural gas–based light-duty vehicle (LDV) scenarios, air emissions increase or show little change in as many stressor categories as they decrease in, whereas in the bus scenarios, life-cycle GHG and SO2 emissions increase while the other air emissions decrease.
- Electric vehicles, both personal and trolley buses, use electricity more efficiently than producing hydrogen from electrolysis, but face major social, technical and economic challenges. Environmental performance is highly dependent on the source of electricity.
- Coal-based electricity for vehicle fuels demonstrate major disadvantages over conventional gasoline or diesel, on a life-cycle basis.
- Nuclear power plants have both positive and negative environmental and social attributes compared to other sources of transport energy. Nuclear power-based systems have near zero life-cycle air emissions, but create radioactive waste with negative safety, security and environmental impacts, some of which last thousands of years.
- Currently, indirect methanol fuel cell vehicle technology demonstrates its ability to nearly eliminate vehicle tailpipe emissions, but currently has limited ability to significantly reduce life-cycle emissions in several categories. This is expected to improve as the technology matures.
- Natural gas vehicles have some of the lowest environmental impacts of any internal combustion engine vehicles and have the potential to be cost-competitive, but would face fuel infrastructure and storage challenges with wide adoption.
- Hybrid Electric Vehicles (HEVs) with internal combustion engines, battery storage and electric drive motors present an opportunity to reduce life-cycle impacts with relatively little change to fuel infrastructure. HEV technology is a relatively simple method of improving overall system performance and could be applied to most vehicle types as an incremental enhancement.
- The benefits and disadvantages of selecting a diesel ICEV over a gasoline ICEV need to be evaluated on an individual basis as there are trade-offs in performance with no clear overall benefit of one over another.
- The use of oilsands instead of conventional oil sources has both benefits and disadvantages. Production of crude oil from oilsands requires more energy input, thus creating higher GHG and NO_X emissions. Conversely, oilsands operations create less volatile organic compounds and

sulphur emissions than conventional oil production. Oilsands operations also concentrate the effects of oil production activities in particular areas.

- Regional considerations are very important to system performance. The shifting of environmental, social and economic burdens and benefits from one region to another are evident in a number of the systems analyzed.
- Full systems thinking and design is critical to ensuring that environmental, social and economic performance is optimized.

Discussion of Results

The following conditions apply to the data used in this LCVA, and provide context for the results that are presented:

- The vehicles assessed are similar in body type and overall efficiency but have not been normalized to include only fuel-related differences. Each vehicle is considered typical for their fuel and class.
- Real-world performance data of both specific operations and entire industrial sectors have been used whenever possible.
- Historical performance data of well-established processes may or may not reflect the performance of these processes currently, or in the future. The most current data available have been used.
- Pre-commercial technologies use information based on the actual performance of prototypes available at the time of data collection as opposed to theoretical performance predictions. The results, therefore, reflect the state of technology development that companies are willing to release at this time.
- Likely performance improvements to technologies, such as legislated emission reductions in vehicles or continuing optimization of emerging products, have not been taken into account. The results represent a “snapshot” in time.
- Light-duty vehicle systems reflect the performance of new vehicles operated over standard dynamometer tests. Bus systems reflect the performance of in-use buses operated both in vehicle fleets and over standard dynamometer tests. This does not take into account performance degradation over time.
- The influence of weather and adverse road conditions has not been accounted for in vehicle performance. Each vehicle type will operate differently under variations in temperature, humidity, precipitation and roadway characteristics.
- The costs of hydrogen, methanol, time-of-use electricity and fuel cell vehicles have been estimated using assumptions based on current technology in a developed market.
- The potential availability of natural resources or equipment has not been evaluated and may limit the possibility of systems being introduced on a large scale. This is a larger concern for systems that have not yet been established in the transportation market.

In any evaluation of competing transportation systems, it is essential to consider the environmental, economic and social aspects of each option. This LCVA brings together both qualitative and quantitative information in its evaluation. The environmental stressors quantified by this LCVA are limited to the following air-based stressor categories:

- greenhouse gases – GHGs
- acid deposition precursors – ADPs
- criteria air contaminants
    - ozone and ground-level ozone precursors – GLOPs
    - particulate matter – PM; secondary particulate matter precursors – SPMPs
    - sulphur dioxide – SO_2

- nitrogen oxides – NO_X
- carbon monoxide – CO

The life-cycle emissions of these stressor categories are presented in Figures ES.2 to ES.4 for light-duty vehicles (LDVs) and Figures ES.5 to ES.7 for buses. These charts have been normalized to show the relative performance of each scenario compared to the incumbent technologies (gasoline ICE LDVs and diesel buses).

Other environmental, social and technical aspects have been evaluated qualitatively. The economic performance of each option is drawn from both historical prices and literature. The economic results do not necessarily represent the current or future costs of each technology within each region. The economic analysis does, however, provide a comparison of potential vehicle and fuel costs for each system. The external costs and benefits of the various systems, such as environmental damage, subsidies or tax revenue, are not evaluated in detail.

The baselines for comparison, or **base case** scenarios, in this LCVA are the incumbent technologies: gasoline ICEs for light-duty vehicles and diesel ICEs for buses. Both of these systems use crude oil from both conventional wells and oilsands mining in the Western Canadian Basin (based on actual production volumes).

The **gasoline ICE** system uses a 2001 Ford Focus for modelling purposes. This vehicle is considered a mid-range performer from a group of compact cars that are considered comparable to other vehicles in this study. The gasoline LDV system has many environmental impacts; the most notable, identified in the analysis, are the following:

- greenhouse gas and criteria air contaminant emissions, which are used as the basis of comparison for the other light-duty vehicles;
- hazardous air pollutants from combustion within several upstream processes, and from oil and gas wells;
- release of liquid pollutants such as gasoline, crude oil, motor oil, refinery and drilling rig chemicals, and automotive coolant; and
- land use and disturbance from oil and gasoline production.

The main social considerations identified include:

- safety hazards of gasoline and its production and distribution infrastructure,
- the aesthetic and land use impacts on people of oil and gasoline production, and
- energy security.

The gasoline LDV system proved to have the lowest vehicle costs of any of the systems, but it is also estimated to have the highest fuel costs of the ICEVs. Existing technologies are faced with ongoing technical challenges to meet stricter environmental or social regulations.

The **diesel ICE** system uses a 2001 Volkswagen Jetta TDI, and a number of in-use diesel buses for modelling purposes. The LDV selection represents one of the few diesel LDVs presently available in North America. A gasoline Jetta is approximately 14% less fuel-efficient than the baseline vehicle, a comparable gasoline Focus. The aggregation of diesel buses is intended to represent bus technology currently operating in urban centres of North America. Compared to the base case, the diesel LDV scenarios have both increasing and decreasing life-cycle air emissions, as shown in Figures ES.2 to ES.4. Within the city regions, ADP, GLOP, PM, SPMP and NO_X emissions are more than 2.3 times those in the gasoline LDV base case. Upstream environmental and social impacts, on the other hand, are less than those of the gasoline LDV system because the diesel ICE LDV requires 31% less crude oil.

The types of environmental, social and technical considerations for the diesel ICE system will be very similar to those of the gasoline ICE system, except diesel vehicles have a longer range and lifetime, lower acceleration, higher noise level, and a more distinct odour. Diesel fuel also has different environmental and safety characteristics than gasoline (as discussed in Sections 5.6 and 6.2.1). The fuel costs for light-duty diesel vehicles are, on average, 33% lower than the gasoline LDV for the three cities studied. However, the capital cost of the diesel LDV is about 10% more than an equivalent gasoline LDV.

The **natural gas ICE** system uses a 2001 Honda Civic GX and a number of in-use natural gas buses for modelling purposes. The LDV selection represents one of the few natural gas light-duty cars currently available in North America. A gasoline Civic is approximately 16% more fuel-efficient than the baseline vehicle, a comparable gasoline Focus. The aggregation of natural gas buses represents technology currently operating in urban centres of North America. Natural gas vehicles have, for the most part, the lowest life-cycle air emissions of the ICEVs. Compared to the base case scenarios, the average energy consumption is 41% lower for LDVs and 8% higher for buses, indicating both relative vehicle and fuel production efficiencies. NGVs are also responsible for reducing air emissions in all of the regions identified except in the bus scenarios, where in-city emissions of CO are higher for natural gas buses than diesel buses (based on test results), and in regions of electricity generation (due to the electricity required for natural gas compression). On a life-cycle basis, emissions are marginally dependent on the electricity source used in each of the provinces. For instance, the effect of using coal as the primary electricity source (in Alberta) instead of hydroelectricity (in British Columbia) raises some stressor categories to a higher level than the corresponding emissions in the HEV system. Therefore, electricity source is an important consideration when designing systems for NGVs.

The natural gas ICE system’s environmental and social considerations are very similar to those of the conventional gasoline and diesel ICE systems, with the following exceptions:

- the environmental and safety characteristics of natural gas are different from those of gasoline or diesel (as discussed in Sections 5.6 and 6.2.1),
- NGVs have shorter range (currently half that of gasoline LDVs and 15% lower than diesel buses) and different refuelling requirements (unique procedures, more frequent refuelling, potential for personal fuel dispensers),
- fuel tanks need to be pressure tested on a regular basis, and
- space is required at the refuelling station for on-site natural gas compression and storage.

On-board natural gas storage densities and refuelling infrastructure are the key technical challenges facing the developers of NGVs. The natural gas Civic has 27% lower fuel costs than the gasoline Focus, on average, but the vehicle cost is between 30% and 60% higher than an equivalent gasoline LDV, although increased production will likely reduce vehicle costs. The natural gas bus has 38% higher fuel costs than the diesel bus, on average.

The **hybrid electric vehicle** (HEV) system uses a 2001 Toyota Prius with a gasoline ICE, battery and electric motor drivetrain; it is independent of the electricity grid, and it uses approximately 30% regenerative braking to recover energy from the wheels. A comparable gasoline Toyota Corolla is approximately 16% more fuel-efficient than the baseline vehicle, a gasoline Focus. In comparison to the gasoline Focus, the Prius HEV demonstrates a 43% reduction in fuel consumption, which directly reduces the upstream environmental and social impacts and the life-cycle GHG emissions. This reduction is possible without changes to the current gasoline supply infrastructure, although the consumer is required to make a larger capital investment in a more complex vehicle with a limited battery lifetime. HEVs do provide better acceleration, greater range and less noise than conventional gasoline LDVs. Criteria air contaminant emissions within the cities of vehicle operation depend on the specific vehicle models being compared. Most tailpipe emissions are lower for the HEV in comparison with conventional gasoline ICE emissions owing to the HEV's regenerative braking and lower fuel consumption capabilities, but in the specific case of the vehicles studied, NO_X emissions increase at the tailpipe by more than 20% for the HEV.

HEV fuel costs are reduced by 43% compared to the gasoline LDV. HEV vehicle cost is approximately 30% to 45% more than an equivalent gasoline vehicle, although increased production will likely reduce vehicle costs.

The **methanol fuel cell vehicle (MFCV)** system uses the NECAR 5 prototype fuel cell vehicle with on-board methanol processing for modelling purposes. Through further vehicle weight optimization, fuel consumption is expected to decrease by as much as 17% from the value used, with a corresponding decrease in life-cycle emissions. As is the same with all of the technology investigated, further advancements in technology development may serve to improve performance beyond predictable levels. A comparable gasoline Mercedes A-Class is approximately 10% less fuel-efficient than the baseline vehicle, a gasoline Focus. The analysis shows that fuel cell vehicles with on-board methanol processing have the ability to reduce urban vehicle emission of criteria air contaminants to near-zero levels, but currently have limited ability to significantly reduce life-cycle emissions in several categories. The result is a shift in some criteria air contaminant emissions from the cities to regions of methanol and natural gas production. The largest increases in upstream air emissions occur for NO_X and ADP, showing average increases of 70% and 10% respectively compared to the base case. Primary energy consumption is on average 9% lower than the base case.

Once again, the upstream environmental and social impacts of methanol production will be similar to those for conventional crude oil production, but the impacts are quite different at the vehicle end. Differences between the two systems include:

- environmental and safety characteristics of the fuel (as discussed in Sections 5.6 and 6.2.1),
- longer start-up time, quieter operation, less distinct odour, and slightly shorter range of MFCVs.

Technical challenges facing the methanol FCV system include:

- retrofit requirements of gasoline equipment to handle methanol,
- potential contamination of fuel cells due to fuel additives, and
- start-up time for on-board fuel processing.

Vehicle manufacturers are targeting fuel cell vehicles to be priced similarly to ICEVs; however, existing academic literature estimates that MFCVs could cost between 13% and 45% more than a comparable gasoline LDV once they have reached mass production. It was estimated that the fuel costs for the NECAR 5 are, on average, the same as the gasoline Focus fuel costs.

The **hydrogen fuel cell vehicle** systems use the NECAR 4a fuel cell LDV and the NEBUS fuel cell bus, both with on-board hydrogen storage. Both vehicles used in this study are prototypes and their performance is expected to improve as the technology matures. A gasoline Mercedes A-Class, comparable to the NECAR 4a, is approximately 10% less fuel-efficient than the baseline vehicle, a gasoline Focus. Gaseous hydrogen is used throughout both of these systems for the majority of analysis.

This study shows that the life-cycle environmental, social, economic and technical aspects of hydrogen fuel cell vehicles are largely dependent on the source of hydrogen. For example, life-cycle air emissions ranged from many times larger than conventional systems (e.g., when producing hydrogen from coal-based electrolysis) to nearly zero (e.g., producing hydrogen from wind, hydroelectric and nuclear-based electrolysis). Steam methane reforming of natural gas demonstrated more moderate changes (some increases and some decreases) in life-cycle emissions when compared to conventional systems, depending on the scale of hydrogen production and the specific location. Compared to conventional vehicles, hydrogen FCV operation has several environmental, social, economic and technical considerations common to each of the hydrogen FCV systems:

- different environmental and safety characteristics of the fuels (as discussed in Sections 5.6 and 6.2.1),
- at this point in development, shorter range, faster acceleration, quieter operation, less distinct odour, and unique refuelling requirements,
- no air pollutant emissions and no motor oil requirements,
- fuel tanks are required to be pressure tested on a regular basis,
- storage and compression at refuelling stations have different aesthetic impacts and space requirements than conventional stations, and
- hydrogen is available from a variety of fossil fuel and renewable resources.

Technical challenges for hydrogen FCVs include:

- reducing fuel cell system costs,
- increasing storage densities of hydrogen or “ground-up” accommodation of pressurized hydrogen tanks into new FCV designs without encroachment into passenger or trunk space,
- reducing hydrogen embrittlement of some metals, and
- development of safety equipment to allow proper handling and storage of hydrogen.

Vehicle manufacturers are targeting fuel cell vehicles to be similarly priced to ICEVs; however, existing academic literature estimates that a hydrogen FC LDV will cost 8% to 38% more in mass production than a comparable gasoline LDV. A cost estimate for a hydrogen fuel cell bus was not completed owing to a lack of existing literature on the subject.

The **decentralized steam methane reforming** system proved to have the widest range in performance, depending on the type of vehicle and its location of operation. It should be noted that the small-scale SMR technology used for this system is still a prototype unit and is claimed to have 8% lower natural gas consumption than many commercial large-scale SMR units, although it also has 47% higher electricity consumption. For the NECAR 4a, life-cycle GHG emissions are up to 45% less than the gasoline LDV system, while for the NEBUS they are 25% less than the diesel bus system, with the potential for greater decreases in most other air pollutants. These reductions are limited to regions of low-emission electricity generation (e.g., British Columbia). This is a result of the electricity requirements for both small-scale SMR units and hydrogen compression. In regions where coal is the primary source of electricity (e.g., Alberta), there is a smaller decrease in emissions, and even an increase in a few stressor categories, such as GHG, PM, SO_2 and NO_X, as shown in Figures ES.3 and ES.6. Generally speaking, the tailpipe emissions of FCVs are much lower than conventional ICEVs, but there is a shift in emissions to upstream processes. In scenarios with high natural gas (bus scenarios) or fossil fuel–based electricity (Calgary scenarios) consumption, the specific upstream regions experience a large increase in emissions.

The decentralized SMR system will have many upstream environmental and social impacts similar to those of conventional oil production activities. One difference will be the need to consider public opinion on SMR units at refuelling stations in populated centres. One of the technical issues identified for the operation of small-scale SMR units at refuelling stations is the flexibility of such units to operate intermittently and at part load.

Based on current estimates, the fuel cost for the decentralized SMR system is estimated to be, on average, 5% less than the gasoline LDV system, but 57% higher than the diesel bus system.

The **centralized steam methane reforming** system has many performance characteristics similar to those of the decentralized SMR system. The primary difference in air emissions between the systems is a result of the large-scale SMR unit requiring 47% less electricity than the small-scale unit. This difference is reflected in Figures ES.2 to ES.7, with a few stressor categories differing as much as 18% from the decentralized to the centralized scenarios. For the most part, however, the centralized SMR-based systems perform similarly to the decentralized-SMR systems.

The other environmental, social and technical considerations of the system are of the same type as the decentralized SMR system, with the following exceptions:

- potential impacts of many small SMR units in populated areas are replaced by the impact of a large SMR unit, likely in a nearby industrial area; and
- there are technical and social challenges associated with hydrogen transport.

The fuel cost for the NECAR 4a using gaseous hydrogen from a centralized SMR plant is estimated to be 22% less than fuel costs for the gasoline Focus, on average, but still 29% greater than the diesel bus. This assumes the hydrogen is distributed via a pipeline.

A system sensitivity analysis investigating the use of **liquid hydrogen** shows a system-wide increase in electricity requirements of 5.4 times those of a gaseous hydrogen system. This increases air emissions in the Calgary scenario by over 60% in all stressor categories, and in the Vancouver scenario by only 1% for the majority of stressor categories. The fuel costs of liquid hydrogen from a centralized SMR plant are estimated to be 60% higher than the cost for gaseous hydrogen. This results in some of the highest fuel costs of any of the fuels assessed (24% greater than the gasoline Focus and twice as high as the diesel bus).

The remaining hydrogen generation systems are based on the **electrolysis** of water. In addition to the system features common to all hydrogen FCVs, the following features are unique to every electrolysis-based system:

- the aesthetic and space requirements of electrolysis units at refuelling stations;
- water consumption; and
- the impacts on wilderness, land use and aesthetics of large areas covered by long-distance electricity transmission lines.

The cost of hydrogen from decentralized electrolysis units using a time-of-use electricity rate of 4.5 cents per kWh is estimated to be 27% higher than the fuel costs for the gasoline Focus and twice as high as the diesel bus fuel costs.

Of the FCV systems investigated, the **wind power–based electrolysis** system demonstrates the lowest environmental impact. With the exception of PM from brake and tire wear, the wind power–based system has essentially zero emissions during operation. Some challenges do exist regarding the availability, cost and site selection of wind turbines.

The **hydroelectricity-based electrolysis** systems in Vancouver and Toronto also have very low operating emissions, again with the exception of PM from brake and tire wear, but significant social and environmental challenges exist when locating large hydroelectric reservoirs – particularly with regard to the effects on plants, animals and people within the area of the reservoir, as well as upstream and downstream from it. These challenges are very site-specific and require detailed investigation on an individual basis. Low-impact hydroelectricity is not expected to have the same challenges.

The **nuclear power–based electrolysis** system also demonstrates extremely low life-cycle air emissions, again with the exception of PM from brake and tire wear. However, there are a number of environmental and social issues associated with the mining of uranium, operation of a nuclear reactor, and impacts of radioactive waste. Nuclear power plants use large amounts of water for cooling, release water effluents, and raise security and safety issues. Handling, storage and disposal of radioactive material present long-term safety and environmental challenges, some of which last thousands of years.

The **natural gas–based electrolysis** system provides both advantages and disadvantages compared to conventional ICEV systems. Tailpipe emissions are completely eliminated with hydrogen FCVs, but there is a corresponding increase in upstream emissions of certain air pollutants compared to conventional transportation systems. In the case of Vancouver and Toronto it was assumed the power plant emissions occur in the same region as vehicle operation, thereby increasing the PM emissions in these regions for the LDV case, with the remaining stressor categories experiencing over 57% decreases. Also for the LDV scenarios, emissions in the upstream regions and for the overall life cycle have almost as many stressor categories increasing as decreasing, compared to the gasoline Focus system. GHG emissions noticeably increase between 13% and 18%. For the bus scenarios, many of the stressor categories increase by more than 50% in the upstream regions, while GHG and SO_2 increase on a life-cycle basis by an average of 64% and 29% respectively. In the LDV scenarios for Calgary, the life-cycle NO_X emissions increase 104%, while in the bus scenario NO_X emissions in upstream regions increase 331%. The reason for this large increase in the Alberta scenario is the anticipation that future natural gas power plants in Alberta are not likely to use selective catalytic reduction (SCR).

The natural gas–based electrolysis system has many other potential environmental impacts, including:

- hazardous air pollutants from combustion, and oil and gas wells;
- release of liquid pollutants such as drilling fluids and crude oil;
- land use and disturbance impacts from natural gas production and electricity generation activities on plants, animals and people; and
- water consumption for power plant operations and water effluent releases into water bodies.

The main social considerations identified include:

- the aesthetic and land use impacts of natural gas and electricity production, and
- natural gas resource depletion.

The **coal-based electrolysis** system has life-cycle air emissions many times higher than any other system studied. The majority of stressor category emissions are more than twice as high as the respective base case scenarios, with the highest being a 19-fold increase in PM emissions in the Toronto bus scenario. The majority of emissions occur at the power plant. This results in a large shift in emissions from Calgary to the areas of rural Alberta surrounding coal-fired power plants. In this case, the air emissions in upstream regions increase to a level from 3.6 to 31 times that of the base case emissions. In Toronto, the power plant air emissions remain in the Windsor–Quebec City region. PM emissions are also very high at the site of coal mining in all coal scenarios.

Other potential environmental and social impacts of coal-based electrolysis are:

- other hazardous air pollutants from combustion (e.g., heavy metals),
- land use impacts of coal mining and electricity generation, and
- water consumption and effluents for power plant operations.

The **electric vehicle** systems use a General Motors EV1 with a nickel metal hydride battery pack and a number of in-use electric trolley buses for modelling purposes. The LDV selection represents one of the few battery electric LDVs presently available in North America, while the aggregation of electric trolley buses is intended to represent bus technology currently operating in urban centres of North America. As in the case of fuel cell vehicles, the life-cycle environmental, social, and technical aspects of electric vehicles are largely dependent on the source of electricity. The following considerations are generic to all electric vehicles:

- safety characteristics of the electricity (as discussed in Section 6.2.1);
- faster acceleration, quieter operation, less distinct odour, , absence of motor oil requirements; and
- impacts on wilderness, land use and aesthetics of large areas covered by long-distance electricity transmission lines.

Considerations specific to battery electric vehicles are:

- the shortest range and longest refuelling times of all the vehicles studied, and
- a relatively short battery lifetime.

Considerations specific to electric trolley buses are:

- the requirement for an extensive electricity distribution infrastructure that requires capital investment and continual maintenance, while it also visually impacts the aesthetics of service areas; and
- limited versatility resulting from reliance on fixed power lines.

Battery electric vehicles have the lowest fuel costs of any of the LDVs. These prices are, on average, 82% lower than gasoline LDV costs using off-peak electricity at 3.55 cents per kWh, and between 53% (Toronto) and 66% (Vancouver) lower using recent residential electricity prices. For buses, the fuel costs range between 42% lower than diesel buses in Vancouver to 10% lower than diesel buses in Toronto. The price of light-duty electric vehicles themselves is roughly twice that of the next most expensive vehicle.

The upstream performance of electric vehicle systems based on wind, hydroelectricity, nuclear, natural gas and coal is identical to the upstream performance of the electrolysis-based FCV systems using comparable sources of electricity, except there is less electricity required by the EV systems. For both the LDVs and the buses, 66% less electricity is required for electric vehicles, to travel the same distance as fuel cell vehicles. This effectively reduces the natural resource consumption in each of the systems compared to electrolysis and reduces the air emissions of both the natural gas- and coal-based systems. In nearly all stressor categories, life-cycle emissions from the natural gas–based system decrease by more than 40% compared to the base cases. The only increase in regional emissions occurs in NO_X emissions for the Alberta trolley bus scenario (62% increase). For the most part, the majority of life-cycle air emissions from the coal-based systems remain higher than or unchanged from the base cases in the majority of stressor categories. In Toronto's surrounding region, emissions for the LDV scenario increase more than three-fold for all stressor categories except CO. In the bus scenario, PM and SO_2 increase 3.4 and 11 times respectively for the same region. In the Calgary scenarios, the air emissions are mostly shifted away from the cities to areas of coal-fired power plants. The majority of upstream stressor category emissions are more than twice as high as the base case scenarios for both LDVs and buses.

Future Work

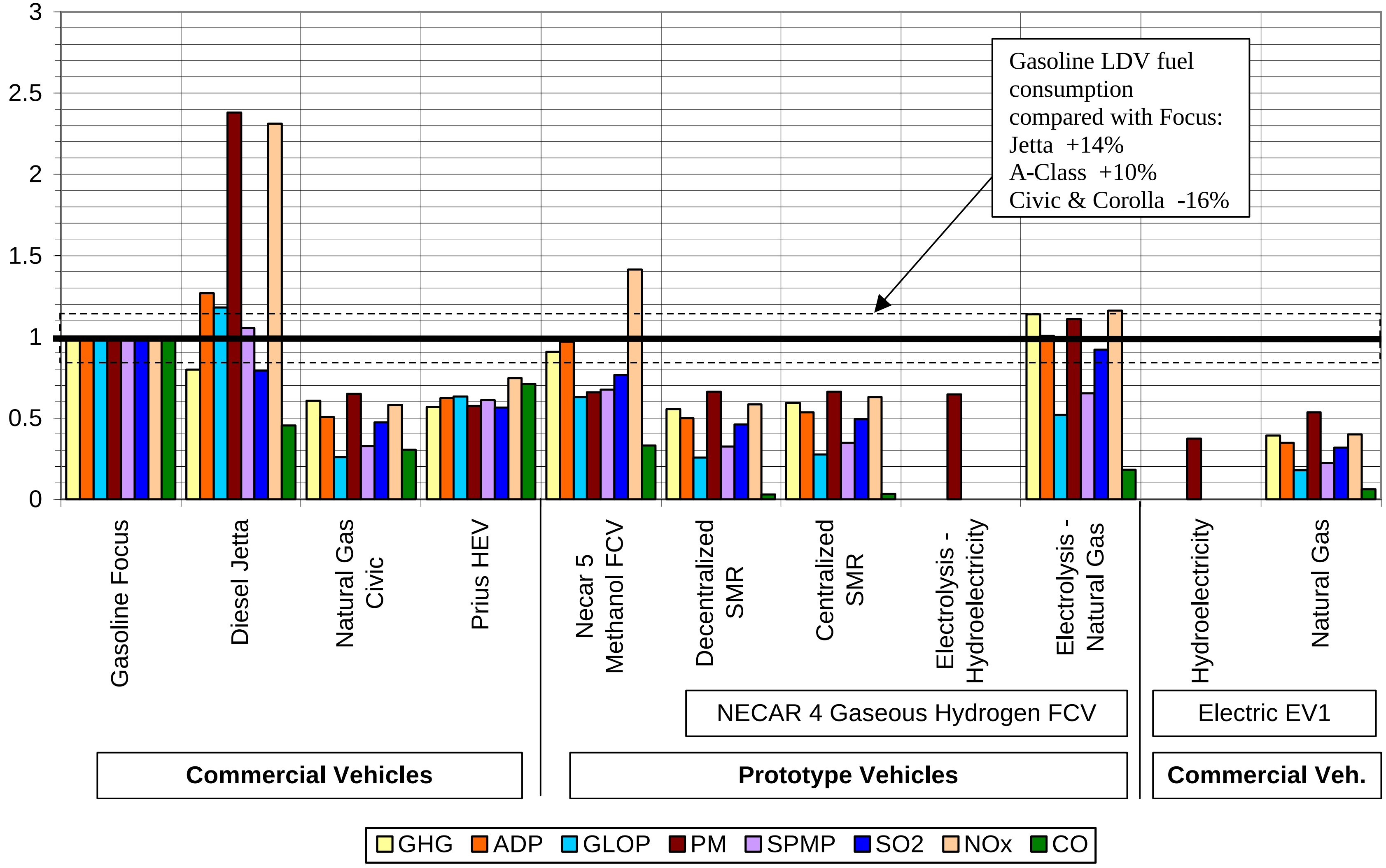
Over the course of this LCVA, many needs and opportunities for further study were identified. The following are recommended areas for further research:

- Hold detailed life-cycle systems design improvement sessions with groups of experts to advance appropriate technologies.
- Evaluate other emerging technologies using the LCVA framework and approach (e.g., vehicles, fuel production and storage of fuels).
- Explore in more detail the environmental, social, technical and economic considerations identified and discussed qualitatively in this study.

- Investigate, in detail, the operating requirements and flexibility for hydrogen refuelling stations and their associated hydrogen production, compression and storage equipment.
- Investigate the effects of vehicle degradation and driving conditions on life-cycle performance.
- Investigate the full transportation system including community-planning aspects to consider how vehicle and fuel-supply systems are affected.
- Utilize the results from this work to assist in developing appropriate strategies and pathways for moving to the most environmentally, socially and economically sound personal transportation systems.
- Utilize the results from this work to assist in designing and implementing appropriate public policy incentives to move towards the best transportation systems.

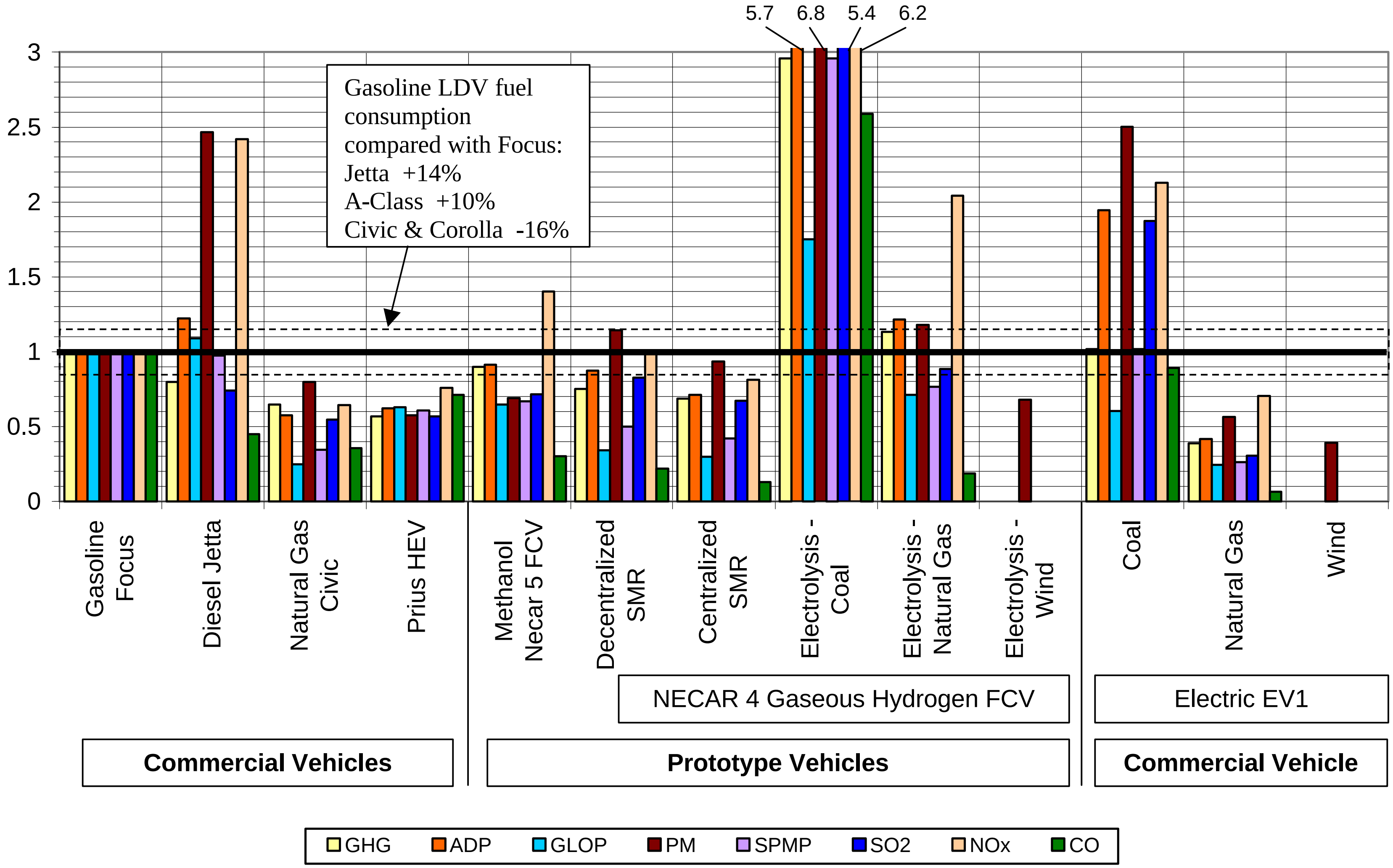
Through the work done in this LCVA, the benefits anticipated from the introduction of low-emission alternative fuel vehicles, such as the fuel cell vehicle, were reinforced. Considerable reductions in regional and life-cycle air emissions are possible through the introduction of a number of vehicle technologies, along with the potential to match or even improve upon the operating performance of conventional vehicles. The hybrid electric vehicle, natural gas vehicle, and methanol fuel cell vehicles all demonstrated the potential to reduce air emissions either in the region of vehicle operation or throughout the life cycle, but by far the largest decreases were observed for systems based on the hydrogen fuel cell vehicle. The electric vehicle systems were also capable of large reductions in regional and life-cycle emissions, but their vehicle range and cost are not expected to be comparable to conventional vehicles. The life-cycle performance of hydrogen fuel cell vehicles did, however, depend greatly on system design. In systems where coal-based electricity was used to provide a significant amount of electricity, system performance changed considerably, and this is probably more harmful to the environment than conventional systems. Before considerable investment in a hydrogen infrastructure is made, proper care must be taken to ensure that the fuel supply systems are properly designed to maximize the benefits of the fuel cell technology, and thus capitalize on the opportunity to move towards a more sustainable transportation system.

Figure ES.2 Normalized Life-Cycle Emissions for LDVs in Vancouver



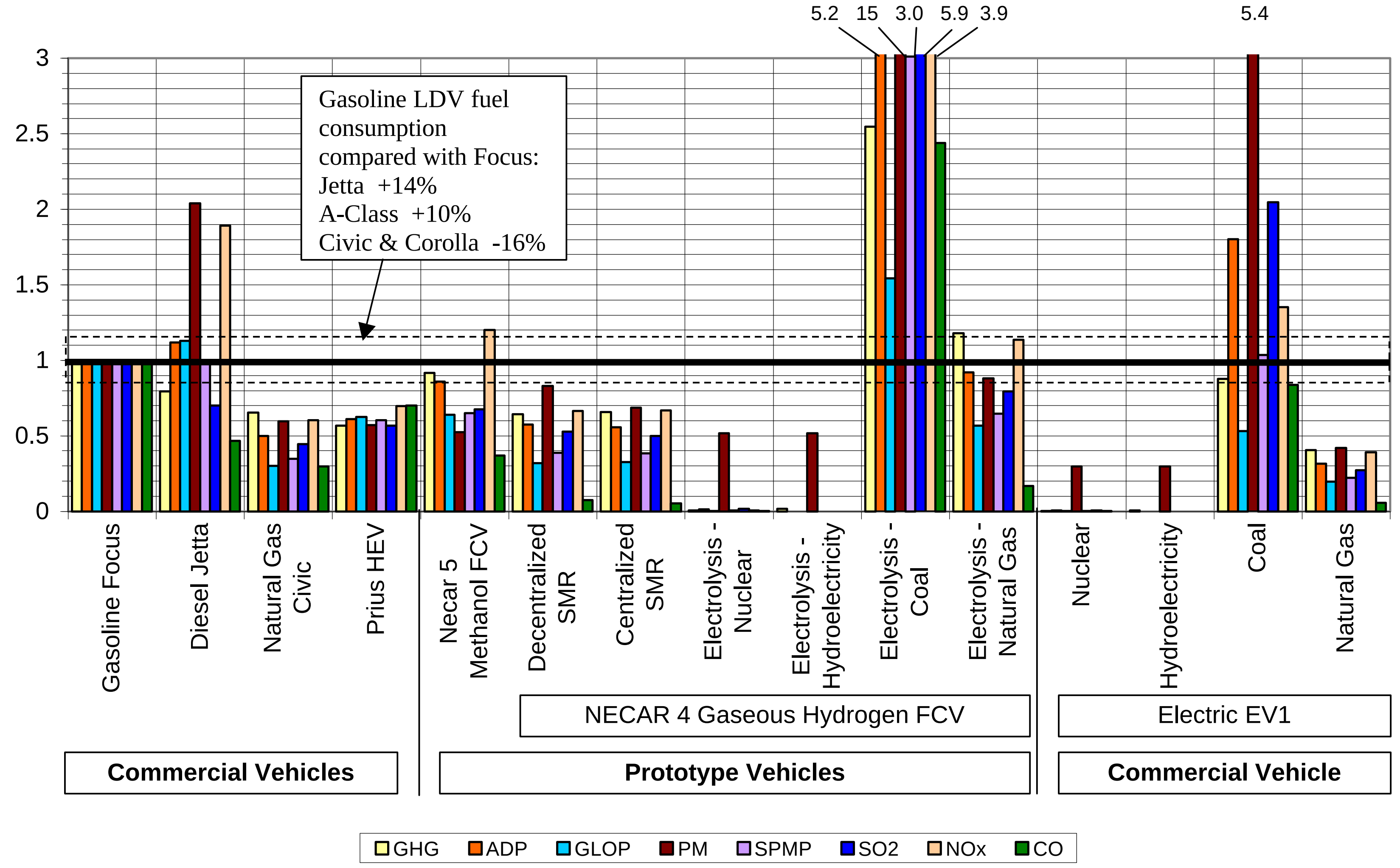
– Methanol FCV expected to reduce fuel consumption by up to 17% through vehicle weight optimization.
– PM emissions from vehicle brake and tire wear present for all vehicle types.

Figure ES.3 Normalized Life-Cycle Emissions for LDVs in Calgary



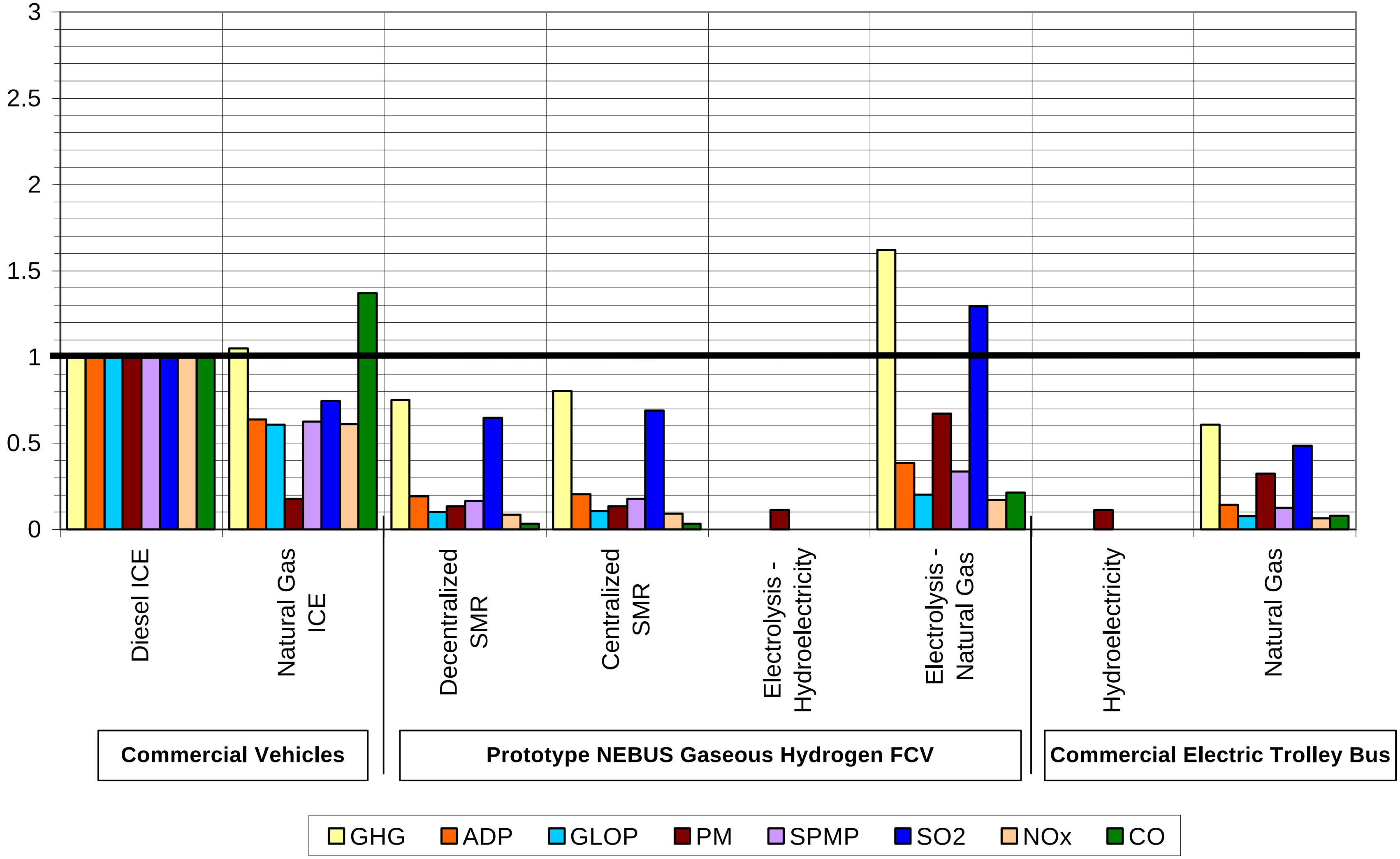
– Methanol FCV expected to reduce fuel consumption by up to 17% through vehicle weight optimization.
– PM emissions from vehicle brake and tire wear present for all vehicle types.

Figure ES.4 Normalized Life-Cycle Emissions for LDVs in Toronto



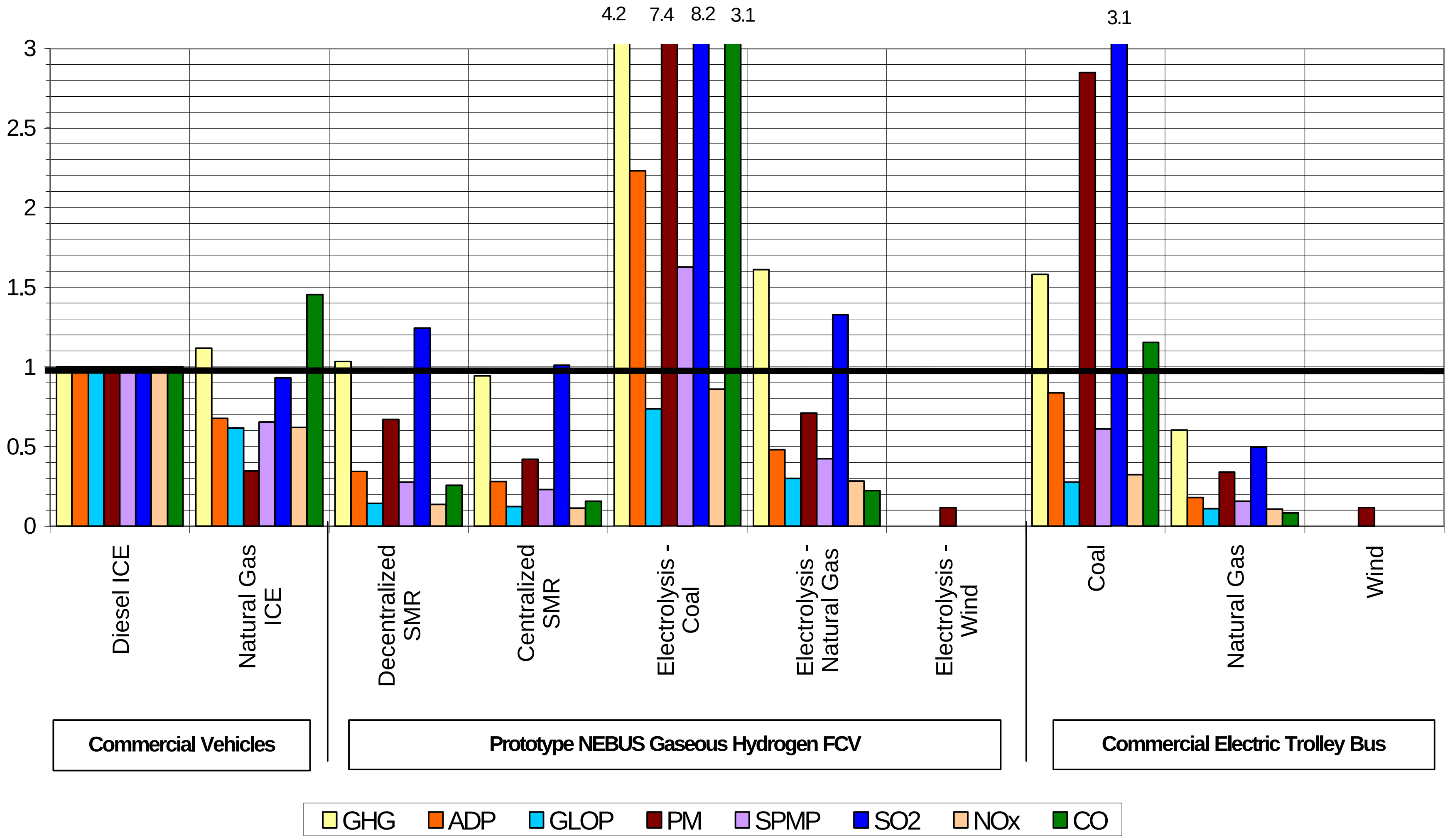
– Methanol FCV expected to reduce fuel consumption by up to 17% through weight optimization.
– PM emissions from vehicle brake and tire wear present for all vehicle types.

Figure ES.5 Normalized Life-Cycle Emissions for Buses in Vancouver



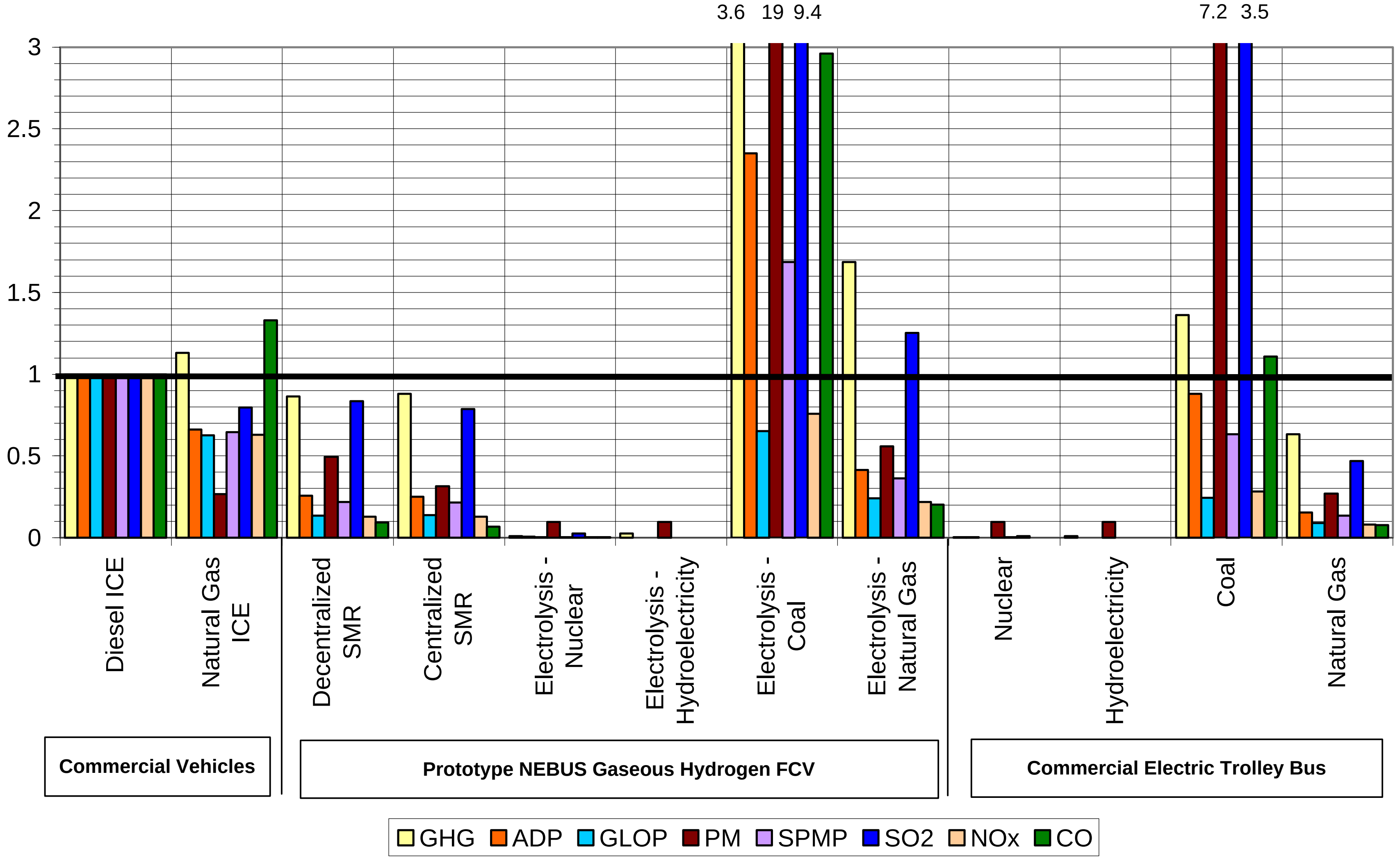
– Hydrogen FCV fuel consumption expected to be lower for current field trial buses.
– PM emissions from vehicle brake and tire wear present for all vehicle types.

Figure ES.6 Normalized Life-Cycle Emissions for Buses in Calgary



– Hydrogen FCV fuel consumption expected to be lower for current field trial buses.
– PM emissions from vehicle brake and tire wear present for all vehicle types.

Figure ES.7 Normalized Life-Cycle Emissions for Buses in Toronto



– Hydrogen FCV fuel consumption expected to be lower for current field trial buses.
– PM emissions from vehicle brake and tire wear present for all vehicle types.

1 Introduction

Urban air quality and the release of greenhouse gases is a growing concern for Canadians. Personal vehicle use is a major contributor to the release of pollutants in urban centres. One potential solution is fuel cell powered vehicles, which have the potential of zero tailpipe emissions. Some countries are interested in increasing energy security through the use of fuel cell vehicles owing to their efficient operation and lack of dependence on crude oil. The challenge of introducing fuel cell vehicles (FCVs) to the market has been taken up by a large number of fuel cell developers and automobile manufacturers around the world, all hoping to establish themselves as prominent suppliers of the next generation of vehicles. A number of technical and financial obstacles need to be addressed before the fuel cell vehicle will become a commercial product – technical operability, competing economically with established conventional vehicles, consumer acceptance, and development of a fuelling infrastructure. Over the past three decades a number of alternative fuels and vehicles have challenged traditional internal combustion vehicles, with relatively little success. Will the fuel cell vehicle suffer the same fate? Or are the potential benefits of the fuel cell great enough to overthrow the century-old incumbent technology of the internal combustion engine (ICE)? If such an investment is to be made by our society, it is of the utmost importance to consider what the impacts of a fuel cell–based transportation system will be compared with the wide range of other technologies currently available.

For any emerging technology to succeed in establishing a significant market share, consumers must believe it to be significantly better than the incumbent technology when considering its impact on their lives. This impact can be broken into three categories: the impact on their economic situation, the impact on their environment and health, and the impact it has on their daily activity and the activities of those around them (socially). If there is no noticeable change in any of these categories, or if there is vast improvement in one at the cost of a large disadvantage in another, then there is little motivation to change. Of course, each of these categories (economic, environmental and social) is complex and cannot easily be quantified into a simple bottom-line comparison, but a fair analysis of each category is required to determine the worth of any technology. The transportation sector is a complex system with various drivers and forces of change, including vehicle manufacturers, government policy, consumer preferences, fuel producers, international environmental concerns, safety standards, environmental protection, emerging technologies, consumer demographics, and consumer wealth. To evaluate technology alternatives for powering and fuelling transportation vehicles, a systems approach is essential.

The purpose of this study is to analyze fuel cell vehicles against conventional ICE vehicles and other alternative vehicles, to enrich the information available for the public, industry and government to make well-informed decisions. The environmental, social and economic aspects of the technologies are compared on a life-cycle basis in order to reflect the impact of consumer choice regarding the vehicle throughout its lifetime and the systems necessary for its operation. This study does not, however, compare personal vehicle use against other modes of transportation such as walking, biking, rail, air travel, or water transport.

1.1 Why Take a Life-Cycle Approach?

Utilizing a life-cycle systems approach to better understand the relative performance of alternative choices in technology is essential. Without a life-cycle approach false conclusions can be drawn. Many European and North American companies have incorporated life-cycle-based techniques into their business and design decision making.

For fuel cell vehicles, the three fuels that have received the most attention (hydrogen, methanol and gasoline) have very different upstream production methods and infrastructure requirements, which will lead to very different life-cycle impacts. Environmentally, the emissions from a low-impact renewable energy source will be very different from those of an oil and gas field. Socially, refuelling a car with hydrogen may require different consumer behaviours than those that now occur with gasoline. And economically, the life-cycle costs of fuels and vehicles vary significantly. Each unique vehicle and fuelling infrastructure scenario will have a unique impact on society, and these impacts need to be considered if well-informed decisions about vehicle technologies are to be made.

1.2 Project Participants

Once the need for this study was identified, Ballard Power Systems Inc., BC Hydro, the Pembina Institute, and Suncor Energy Inc. decided to bring their expertise together to more thoroughly investigate the life-cycle implications of various vehicle and fuel supply scenarios. Coordination of the project, system modelling, and results presentation were completed by the Pembina Institute, while data collection and technical review were accomplished by all of the project participants. An external review of the final public report was also performed. Members of the technical steering committee and the external reviewers are listed in Appendix A. Together, the project team used the Pembina Institute’s Life-Cycle Value Assessment (LCVA) methodology to analyze the environmental, social and economic aspects of the selected scenarios. More information regarding the LCVA methodology is presented in Section 3.

1.3 Previous Work

There is a growing volume of literature concerning fuel supply options for fuel cell vehicles and it is important to distinguish how this LCVA fits in with existing work. This study builds on a previous study performed by the Pembina Institute and the David Suzuki Foundation (Jamin 2000), confirming that the choice of vehicle and fuel supply options has a significant implication for the life-cycle greenhouse gas emissions of mobile fleets. The study also identified several technical challenges facing the introduction of fuel cell vehicles. This preliminary study did not, however, quantify other environmental, social or economic impacts.

Other organizations that have completed fuel-cycle assessments of greenhouse gas emissions associated with fuel cell vehicles include General Motors, the Massachusetts Institute of Technology, Methanex, Levelton Engineering Ltd., and the Argonne National Laboratory. All of the aforementioned studies attempt to predict the future performance of fuel supply and vehicle systems. As expected, the results vary depending on the assumptions being made by the project teams. This study takes a unique approach to comparing vehicle and fuel systems by eliminating the bias and uncertainty of projecting future technology improvements. The result is an LCVA that compares the current state of technologies and accurately demonstrates their relative performance. The main disadvantage of such an approach is the comparison of technologies at differing levels of maturity. Of course, this also occurs in the other studies where levels of technology maturity are assumed. The effect of maturity level on the outcomes of the study is discussed further in Section 3.2, “Identification and Selection of Systems Evaluated.”

1.4 Description of Report Sections

This report follows the progression of a typical life-cycle value assessment. First, the background of the project is outlined in Section 2. Next, the goal of the project is defined, including the systems to be evaluated and the LCVA audience, in Section 3. Section 4 describes the qualitative scoping process, where each system is further defined using a functional unit, process flow map and a system boundary, and each Unit Process is investigated briefly.

Environmental considerations are discussed in Section 5. This section starts by describing the environmental stressor categories selected for detailed assessment, followed by a brief environmental context regarding the geographical regions considered. The results of the system modelling for both light-duty vehicles and buses are then discussed as they relate to their respective base case scenarios. Lastly, the environmental stressor categories identified in the scoping process as important considerations but were not quantified are described briefly.

Sections 6 and 7 contain descriptions of the social and technical considerations that were identified in the scoping process, while Section 8 contains a comparison of various economic costs for each system evaluated, including fuel, vehicle and external costs. The report closes with a summary of conclusions, recommendations and areas for future work in Sections 9, 10 and 11 respectively.

Appendix A contains a list of contributors to the project. Appendix B contains a description of each unit process within the LCVA. These are intended to assist the reader in understanding the details of the systems modelled. Appendix C contains the outputs from the LCVA model. Appendix D contains a summary of the assumptions used in the economic analysis.

2 Background

2.1 Future Transport Technologies

The Canadian automotive manufacturing sector's total shipments amounted to approximately CAN$90 billion in 1998. (APEC web site, 2002) With a global move towards lower emission vehicles, manufacturers have a large incentive to introduce vehicles that meet the emerging requirements of both consumers and government regulators. The attempt to meet these standards has resulted in a wide range of vehicle technologies and technology providers, each with advantages and disadvantages when compared with conventional technologies. There are also a number of emerging technologies that require support from various parties, including government, investors and technology developers, in order to become commercial products. It is a challenge for all involved to objectively evaluate the variety of technologies available and make a well-informed decision on which ones to support.

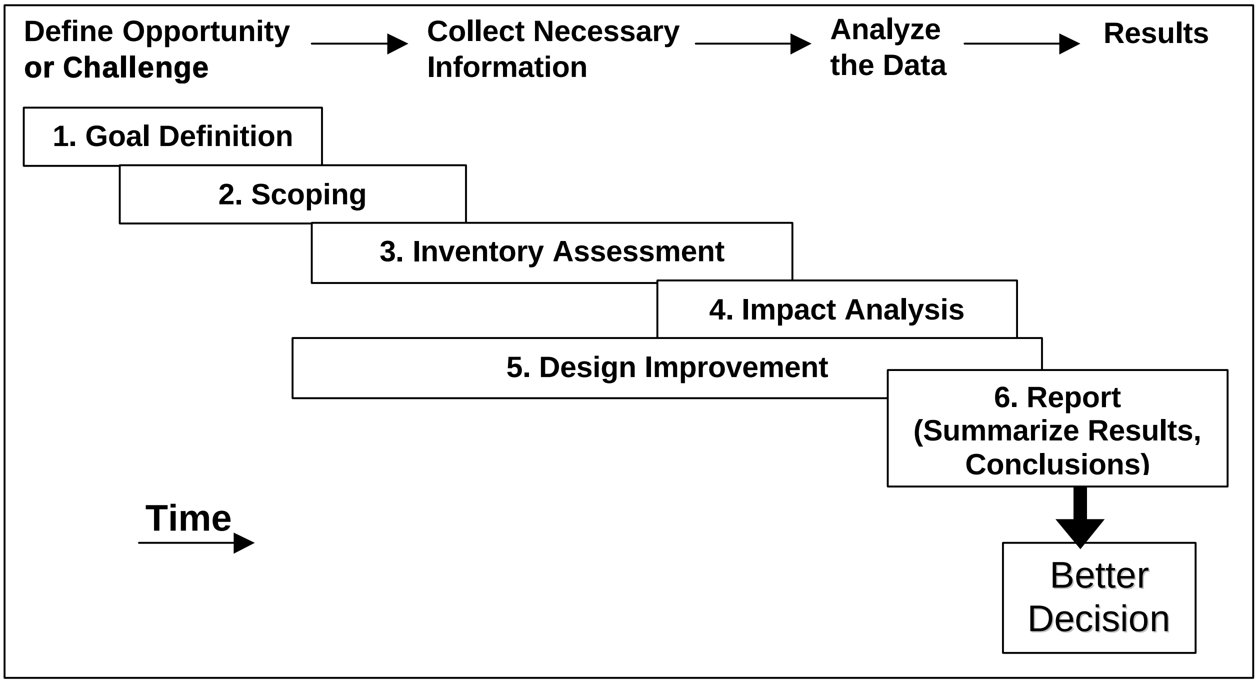
The impetus for a rapid introduction of FCVs and a fuelling infrastructure comes from many sources. The California Air Resources Board has accelerated the advancements of several vehicle technologies as a result of their zero emission vehicle incentive programs, designed to improve the urban air quality within the state. The push towards lower emission vehicles is reflected throughout North America as the federal governments in both the United States and Canada move towards harmonizing their automobile emission and fuel standards to increasingly strict levels. The Canadian federal government has also funded initiatives to accelerate the commercial acceptance of FCVs as a way to reduce national greenhouse gas emissions (GHGs). For the United States, it is evident from the oil crisis of the 1970s and more recent events at the beginning of the 21st century that a decreasing dependence on oil from the Middle East is important to ensure a stable and secure economy and lifestyle. Some progressive companies in the marketplace are also working to become more sustainable thus mitigating specific risks and increasing their profitability. This may also increase their appeal to certain investors and customers. Resultantly, technology developers are responding to government, consumer and corporate demands for vehicles that are environmentally friendly and cost competitive and that offer enhanced performance.

Several alternative vehicle technologies have emerged from the laboratory and the testing grounds to address the growing needs of government and consumer. Natural gas vehicles, liquefied petroleum gas (propane) vehicles, ethanol or ethanol-blended vehicles, methanol or methanol-blended vehicles (IC or FC powered), gasoline or naphtha fuelled FCVs, electric vehicles, hydrogen fuelled vehicles (IC or FC powered), and hybrid electric vehicles, among others, are all potential challengers to the incumbent technologies of conventional gasoline and diesel fuelled IC engine vehicles. Each of these vehicle technologies can use a variety of fuel production pathways depending on the type of fuel selected, the point of purchase, the cost of production, the resource availability, and a myriad of other factors that will all have an affect on the economic, environmental and social impacts of the entire system. It is first the automobile manufacturers and fuel suppliers who make these choices available to consumers, then it is up to the consumer to decide what these impacts will be when selecting a vehicle, its fuel and method of operation. The impacts will occur along the entire life cycle of the vehicle and fuel production, use and disposal.

2.2 An Introduction to the LCVA Methodology

The Life-Cycle Value Assessment (LCVA) methodology used in this study was developed by the Pembina Institute in co-operation with several of Canada's leading energy companies. This tool extends the traditional life-cycle assessment to include economic and social implications in addition to analysis of environmental issues. A systematic analysis, LCVA examines the planning; production; consumption; and recycling, decommissioning or disposal of a service or product. It can be focused on financial and/or technical risk analysis, identification and development of system improvements (environmental, social, design), or stakeholder issue identification.

Figure 2.1 The LCVA Process



The LCVA methodology begins by clearly defining the decisions to be made, the questions to be answered, and the systems to be analyzed and/or compared (**Goal Definition**). **Scoping** consists of developing a life-cycle activity map of planning, production, use and disposal functions, and organization of these activities into discrete and convenient units of analysis. Financial, energy and material inputs and outputs are then identified qualitatively for each unit process. The relative importance of identified impacts, and the stated objectives of the LCVA, is used to determine which life-cycle stages, and which environmental, financial and social issues are likely to provide the most valuable information for improved decision making. Only these parameters are selected for quantification, effectively setting the system boundaries for the LCVA.

Inventory Assessment involves collecting and validating data to quantify the inputs and outputs of selected life-cycle stages. Data are compiled and modelled to provide aggregated results for various scenarios and systems to answer the key questions outlined in the LCVA goal definition. Results are assessed in terms of their relative impacts and significance in the **Impact Analysis**.

Scoping, Inventory Assessment and Impact Analysis all offer opportunities for **Design Improvement**. As a stand-alone effort, it offers a systematic approach to find opportunities to reduce the negative social, economic and environmental impacts throughout the full life-cycle system. Ideologies such as “total quality management,” “pollution prevention,” and “design for environment” can be incorporated into an LCVA committed to a full design improvement stage.

Summarized results, conclusions and recommendations are compiled in a **Report** or presentation addressing those opportunities or challenges identified in the Goal Definition.

3 Goal Definition

3.1 Objectives

The principal objective of this LCVA is to quantify and evaluate the life-cycle environmental factors of a wide range of technically advanced (i.e., poised for commercialization) options for operating fuel cell vehicles in Canada. The selected fuel cell vehicle technologies are compared with conventional ICE vehicles as well as with other emerging vehicle alternatives that have reached the commercial market. In addition this LCVA will qualitatively identify technical design challenges and social impacts on consumers and society in general, and review the current economics of fuel cell vehicles and fuelling infrastructure.

Specific questions to be answered by this LCVA include:

I. How does the life-cycle environmental performance of various fuel supply options for fuel-cell vehicles compare with each other, with conventional vehicle fuels, and with select alternative fuels?

II. What technical challenges and barriers to implementation exist or may exist in the future for each fuel supply scenario?

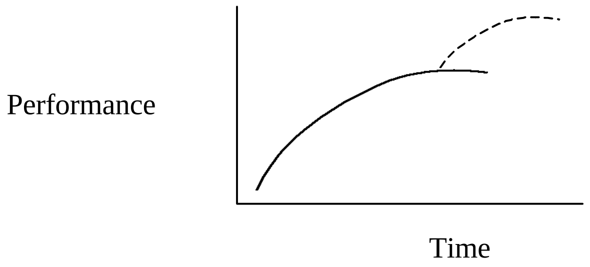
III. What potential social benefits and/or costs exist or may exist in the future for each fuel supply scenario?

IV. How do the life-cycle fuel costs (dollars per kilometre of fuel service) of various fuel supply options for fuel cell vehicles compare with each other, with conventional vehicle fuels, and with select alternative fuels?

3.2 Identification and Selection of Systems Evaluated

Technologies at or near commercial implementation that create systems that apply to a wide range of the Canadian population were selected for evaluation within this LCVA. As with any study comparing different technologies, the level of maturity of the technology influences the results. The generic technology innovation curve in Figure 3.1 shows how technology performance typically improves as time goes by. The level of innovation is usually very high for newly discovered technologies and reaches a plateau once several generations of development have resulted in a highly optimized design. The dotted line in Figure 3.1 represents the potential for a new technology curve to begin if a major breakthrough in innovation occurs, essentially resulting in a new technology. The technologies compared in this LCVA currently exist at different places along the technology innovation curve. At a minimum, all of the technologies have been developed past the laboratory stage and are being demonstrated in working prototypes. For the most part, only the fuel cell vehicles and some of the hydrogen production technologies are at this stage. Other technologies have reached a level of performance that has resulted in their commercialization. Some have been at the commercial stage for many years and are expected to have only incremental performance improvements in the future.

Figure 3.1 Generic Technology Innovation Curve



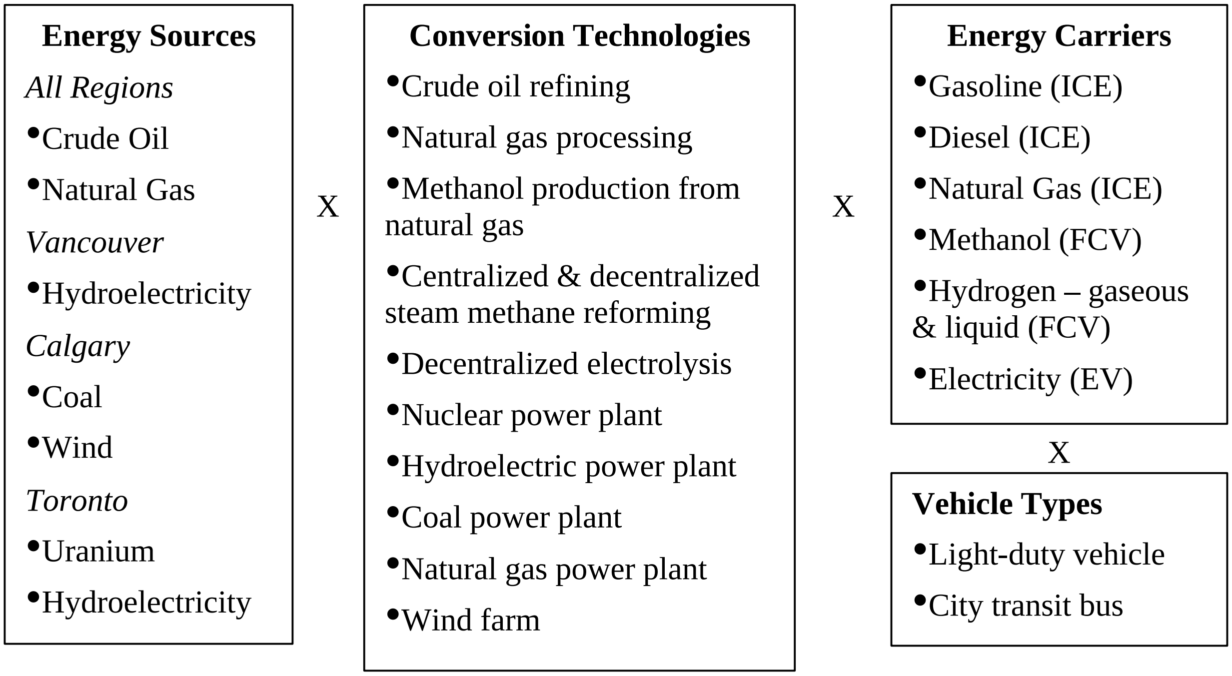
This study compares the current state of technology, representing a “snapshot” in time rather than attempting to predict future performance. Since some of these technologies have not yet fully matured, the relative performance of the vehicle and fuel supply systems is expected to change in the future. The performance of not-yet-commercialized technologies is expected to have the greatest potential to improve, given their relatively low level of maturity. The only exception to this approach occurs in the economic assessment, where the actual financial costs of emerging technologies are much more difficult to determine and properly compare with established technologies. As a result, the hydrogen- and methanol-based systems use publicly available literature to predict the respective fuel, vehicle and infrastructure costs assuming high-volume manufacturing efficiencies are used.

A summary of the energy and technology types evaluated within this LCVA appears in Figure 3.2, while Table 3.1 lists the fuel and vehicle combinations evaluated. Several other technologies were considered by the technical steering committee, but ultimately rejected; they are listed in Table 3.2. The reasons for exclusion are also presented in the table.

The cities of Calgary, Toronto and Vancouver were chosen because they represent large transportation fuel markets across Canada with very different upstream energy resources. Location-specific systems are evaluated because theoretical, generalized systems would require complex assumptions in order to apply real-world data to the imaginary systems. Furthermore, the results from analysis of generalized systems would ultimately not apply to any real situation, thereby limiting the usefulness of the study.

In total, 72 different scenarios (unique city, vehicle and fuelling pathway combinations) are evaluated in this study. Since these scenarios are being evaluated for application in three Canadian cities, the results may or may not be transferable to other regions of the country or the world.

Figure 3.2 Energy and Technology Types Selected for Assessment



3.3 Time and Resources

The limiting factor in any LCVA is the amount of time and resources allocated to performing the assessment. This can range from a minimal amount of resources to obtain a quick survey of the critical issues to a highly detailed study that requires copious specific information in order to quantify a number of the system impacts.

This LCVA was completed over the course of 18 months and involved a number of people from each of the project participants at different stages within the project. Several external contacts within industry and government also contributed to the project by providing information on critical technologies and processes, and giving feedback on the final public report. A list of the project contributors appears in Appendix A.

Table 3.1 Unique Systems Evaluated Within the LCVA

System	Fuel Type	Source of Fuel	City	Vehicle Type(s)
A (HEV = AA)	Gasoline	Alberta average crude oil. *Sensitivity: synthetic crude from oilsands in the Calgary IC LDV scenario.*	Calgary, Toronto, Vancouver	i. Compact LDV - IC ii. Compact LDV - HEV
B	Diesel	Alberta average crude oil.	Calgary, Toronto, Vancouver	i. Compact LDV - IC ii. Bus - IC
C	Natural Gas	Alberta average natural gas production.	Calgary, Toronto, Vancouver	i. Compact LDV - IC ii. Bus - IC
D	Methanol	On-board fuel processing of methanol produced from Alberta natural gas.	Calgary, Toronto, Vancouver	i. Compact LDV - FC
E	Hydrogen	Decentralized reforming of natural gas.	Calgary, Toronto, Vancouver	i. Compact LDV - FC ii. Bus - FC
F	Hydrogen	Centralized reforming of natural gas. *Sensitivity: liquefied hydrogen in the Vancouver and Calgary scenarios.*	Calgary, Toronto, Vancouver	i. Compact LDV - FC ii. Bus - FC
G	Hydrogen	Decentralized electrolysis from nuclear powered electricity.	Toronto	i. Compact LDV - FC ii. Bus - FC
H	Hydrogen	Decentralized electrolysis from hydroelectricity.	Toronto, Vancouver	i. Compact LDV - FC ii. Bus - FC
I	Hydrogen	Decentralized electrolysis from coal powered electricity.	Calgary, Toronto	i. Compact LDV - FC ii. Bus - FC
J	Hydrogen	Decentralized electrolysis from natural gas powered electricity.	Calgary, Toronto, Vancouver	i. Compact LDV - FC ii. Bus - FC
K	Hydrogen	Decentralized electrolysis from wind powered electricity.	Calgary	i. Compact LDV - FC ii. Bus - FC
L	Electricity	Ontario nuclear power	Toronto	i. Compact LDV - EV ii. Bus - trolley
M	Electricity	B.C. or Ontario hydroelectricity	Toronto, Vancouver	i. Compact LDV - EV ii. Bus - trolley
N	Electricity	Alberta or Ontario coal	Calgary, Toronto	i. Compact LDV - EV ii. Bus - trolley
O	Electricity	Natural gas combined cycle gas turbine (CCGT).	Calgary, Toronto, Vancouver	i. Compact LDV - EV iii. Bus - trolley
P	Electricity	Alberta wind power	Calgary	i. Compact LDV - EV ii. Bus - trolley

LDV = light-duty vehicle e.g., Ford Focus, Toyota Prius, etc.
Bus = heavy duty public transit bus
FC = fuel cell
IC = internal combustion
EV = electric vehicle
HEV = hybrid electric vehicle

Table 3.2 Technologies Not Evaluated

Technology	Reason for Exclusion from LCVA
Fuel cell battery electric vehicles	Current state of the technology does not allow for a comparison with selected LDV and bus applications. No data are currently available on the performance of this vehicle. To be considered in future work.
Solar powered electricity for electrolysis	Cost differential with other sources of electricity in Canada considered too large. Current use of photovoltaic electricity is limited within Canada.
Hydrogen IC engine	No data are currently available on the performance of original equipment supplier vehicles. To be considered in future work.
Carbon black and hydrogen	The technology is not advanced enough to provide sufficient information/data for evaluation.
Bio-hydrogen for FCVs	The technology is not advanced enough to provide sufficient information/data for evaluation.
Bio-methanol for FCVs	Not a commercially available fuel; limited data available.
Bio-diesel fuel for ICEs	Supplies and Canadian experience of bio-diesel are currently minimal.
Indirect methanol FC buses	Consensus within steering committee that methanol storage on buses is unlikely for Canadian urban applications when compared with compressed hydrogen storage.
Direct methanol FCVs	Current state of the technology does not allow for a comparison with selected LDV and bus applications. No data are currently available on the performance of this vehicle. To be considered in future work.
On-board fuel processing of gasoline, naphtha, ethanol, etc. in FCVs	Current state of the technology does not allow for a comparison with selected LDV and bus applications. No data are currently available on the performance of this vehicle. To be considered in future work.
Ethanol for ICEs	Ethanol is a competitor to hydrogen fuelled vehicles; however, time and resources to investigate the potential of large-scale production of lignocellulose-derived ethanol in Canada are not sufficient. May be considered in future work.
Direct-injection gasoline IC engine	Not currently available in North America. Potential for increased IC efficiency, but fuel quality may limit application.
Methane from landfills	Potential supply small compared with vehicle market demand.
Coal bed methane	Not currently a significant source of methane in Canada.
Electricity or hydrogen from low-emission coal	The technology is not advanced enough to provide sufficient information/data for evaluation.

3.4 Audience

The audiences identified for this LCVA are included in Table 3.3 along with their targeted area of interest.

Table 3.3 Identified LCVA Audiences

Audience Group	Area of Interest
Policy makers at the municipal, provincial and federal government levels	Government policies have the ability to influence the transportation sector by setting guidelines, policies and performance targets and incentives. An understanding of the relative performance of different transportation systems is required to ensure that policies achieve the government's mandate of protecting the health and environment of Canadian citizens; ensuring safe, efficient and convenient transportation systems; and enabling the economy to function smoothly.
Fleet operators in government, transit authorities and the private sector	Fleet operators own and operate a significant number of vehicles and therefore collectively have the ability to influence the market acceptance of new technologies. A clear understanding of the impacts of different fleet vehicles is required to ensure that fleet operators are able to provide reliable, cost-effective transportation to a large group of users while working towards additional goals of reducing their negative impact on the health and environment of the public.
Consumers within the general public	Individual consumers make up the largest portion of vehicle users today and are continually shopping for improved product performance. When considering the purchase of a new vehicle or when refuelling a vehicle, consumers consider price and on-road performance, but an increasing section of the population also considers the impact their purchase has on the environment. By seeing the life-cycle impacts of vehicles and fuels presented in a concise manner, the consumer is able to make a well-informed choice.
Technology developers and marketers	Technology developers may find the most direct value from this life-cycle value assessment. The ability to identify the major impacts of their product on the lives of their customers and society as a whole before it is introduced allows developers to better design their product and increases their chance of success.
Energy producers and fuel suppliers	Like the technology developers, fuel suppliers have a considerable impact on the daily life of their customers and are well advised to investigate the entire range of issues surrounding the life-cycle of their product.
Investors	Investors choose companies and technologies based on their potential to provide financial returns. This is dependent on a wide range of factors. Fuel cell technology is considered to be the clean and efficient alternative to current systems. If investors are counting on this to be a driving force for profit potential, then understanding the full life-cycle environmental performance is essential to their investment decisions. There is also a growing investor population focusing on socially responsible or ethical companies.

4 Qualitative Life-Cycle Scoping

4.1 Functional Unit

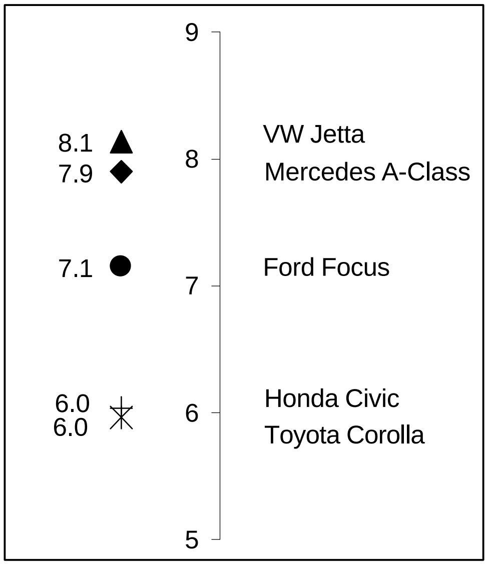
The functional unit in any LCVA is the basic unit of comparison that is common among all systems being evaluated. Each system must produce the identical end products or services to ensure a fair comparison. For both the light-duty vehicles and the buses, 1000 km of on-road travel is the functional unit that has been selected for this study. This functional unit also allows the results to be scaled to reflect the impact of operating a vehicle over the course of a number of years and for a fleet of vehicles.

The “quality” of the functional unit is another important factor to consider ensuring that an appropriate comparison between systems is made. For both vehicle types, various performance characteristics were compared during vehicle selection to ensure that a like-to-like or “apples-to-apples” comparison was made.

The light-duty FCVs for which data were available for analysis were Ford’s P2000 FCV (gaseous hydrogen) and DaimlerChrysler’s NECAR 4 (liquid hydrogen), 4a (gaseous hydrogen) and 5 (methanol). The P2000 is based on a Partnership for the Next Generation of Vehicles (PNGV) design and uses advanced technologies to increase its fuel efficiency. These technologies are not comparable to those available in current production vehicles; therefore, the P2000 was not used in the analysis. The NECARs are based on the Mercedes A-Class vehicle available in Europe.

The remaining vehicles selected for the study are intended to represent a typical vehicle within a class comparable to the aforementioned fuel cell vehicles. The specific diesel, hybrid electric, natural gas and electric vehicles were selected because they were the only vehicles available within North America that had data available to the project team and that provide adequately comparable performance. A Honda Civic HEV has recently become available to the consumer (2002); however, specific emission data were not available at the time the data inventory was being completed. The gasoline vehicle, on the other hand, was selected as a mid-range performer from a group of compact cars that are considered comparable to other vehicles in this study, as shown in Figure 4.1.

Figure 4.1 Fuel Consumption of Compact Gasoline LDVs (litres/100 km)



Notes:

All vehicle models are from 2001.

All values are based on standard driving cycles and have not been adjusted to reflect real-world driving.

Mercedes A-Class data are based on the New European Driving Cycle.

Table 4.1 shows a comparison of the light-duty vehicles selected based on data available from the manufacturers and independent tests. As expected, the vehicles selected do not provide identical performance to the operator in all categories, particularly vehicle range, since it is not possible to find identical vehicles for all fuel types in the real world. These differences in performance should be kept in mind when comparing vehicle options. Performance differences that are not attributed to fuel type will influence the results, which is a valid element of comparison; however, the non-fuel-related differences are not expected to affect the overall conclusions.

Fuel consumption and emission data are based on dynamometer testing of new vehicles over a combined city and highway driving cycle. For the majority of vehicles, the US EPA federal test procedure (FTP) for combined city and highway driving was used. This combined cycle is based on 55% city driving by distance. For the NECAR 4, 4a and 5 FCVs, only data from the New European Driving Cycle (NEDC) was available and thus was used to estimate the vehicle's fuel consumption. A comparison of the combined city / highway fuel economy of several compact cars for both the FTP and NEDC driving cycles revealed that the difference between cycles was within 5% for most vehicles.

In order to obtain the most accurate quantification of life-cycle impacts for 1000 km of travel, it would be ideal to use actual on-road performance data for the vehicles. Standardized dynamometer tests typically result in lower fuel consumption than is experienced on the road, mainly because of the more aggressive driving habits of the average driver. The US EPA estimates a 10% increase in fuel consumption in LDVs for city travel, and a 22% increase on the highway relative to dynamometer tests. Unfortunately, it is very difficult to obtain reliable and consistent on-road performance data for a wide number of vehicles. The US EPA on-road estimates are one method of reflecting this difference, but since data from both the EPA and NEDC driving cycles are being used, it was decided that adjustment of the vehicle data would add to the complexity of using both cycles in this comparative analysis. Ultimately, the quantified values in this LCVA represent a somewhat reduced estimate of typical on-road performance. The comparative analysis, however, remains accurate. The results of the new MOBILE 6 emission factor model, which better addresses on-road performance, are not yet available to help address this issue.

A further disadvantage of using dynamometer tests of new vehicles is the inability to reflect the likely change in vehicle performance over time. The degradation of efficiency and emissions control technologies of conventional vehicles is well documented. It is also reasonable to expect that emerging technologies will decrease in performance as they age. This has the potential to greatly alter the relative life-cycle performance of the various systems evaluated. Unfortunately, owing to the complexity and lack of data available to assess the influence of vehicle degradation, it was not investigated in detail.

Inequalities in vehicle performance are also likely to occur along with changes in weather and road conditions. The extreme climatic shifts present throughout Canada require vehicles that are durable enough to operate reliably over a wide range of temperatures, humidity, precipitation, and roadway characteristics. Each vehicle type will handle these conditions differently and may result in very different life-cycle performance than under ideal conditions. The influence of operating conditions on life-cycle performance was not investigated in detail, but should be considered for future analysis.

Table 4.1 Light-Duty Vehicles Used In The LCVA

Performance Feature	Units	Ford P2000	NECAR 4	NECAR 4a	NECAR 5	Ford Focus (gasoline)	VW Jetta TDI (diesel)	Toyota Prius (gasoline HEV)	Honda Civic GX (natural gas)	GM EV1 (NiMH EV)
Range	km	160	450	200	500	660	1085	990	322	103
Maximum power rating	kW	67	50	53	55	82	66	85	N/D	102
Acceleration 0-100 kph	s	12	N/D	N/D	N/D	N/D	12	N/D	N/D	9
Top speed	Km/hr	128	155	155	155	N/D	N/D	168	N/D	129
Length	m	4.75	3.57	3.57	3.57	4.27	4.38	4.31	4.43	4.31
Mass	kg	1514	1300	1300	1700	1165	1349	1255	1220	1320
Seating capacity	#	5	5	5	5	5	5	5	5	2
Payload capacity (incl. passengers)	kg	N/D	450	450	450	N/D	440	N/D	N/D	N/D
Payload capacity	litres	N/D	N/D	N/D	N/D	3030	N/D	2843	2761	2055

N/D – no data available VW – Volkswagen TDI – turbo direct injection GM – General Motors NiMH – nickel metal hydride

A standard 12.2 m urban transit bus was selected as the basis for comparing the different bus technologies. The fuel cell bus used in the analysis is the DaimlerChrysler NEBUS, which uses a Mark 700 series fuel cell stack. This technology is one generation behind Ballard's current Mark 900 series fuel cells with increased power density. Therefore, the final results will not reflect the most recent technology developments. They do, however, provide a starting point for evaluating the relative environmental performances of bus technologies. Table 4.2 compares the typical characteristics from each bus technology for illustrative purposes.

A number of data sources were available regarding bus emissions and fuel consumption; however, finding comparable data for fuel cell buses proved to be very challenging. The fuel consumption for the diesel, natural gas and fuel cell buses is based on field trials performed under load and along identical service routes in the city of Esslingen, Germany. This proved to be the only directly comparable data available at the time of data collection. The electric trolley bus fuel-consumption estimates were taken from actual performance data provided by Coast Mountain Bus Lines, the urban transit authority in Vancouver, British Columbia. Given that the diesel bus fuel consumption data provided by Coast Mountain Bus Lines for Vancouver are within 4% of the Esslingen measurements, it is assumed that the electric trolley bus data are comparable to the Esslingen data for the other bus types. The tailpipe emissions data used for analysis are based on a conglomeration of a number of buses and data sources, based primarily on dynamometer testing over the Central Business District driving cycle. The emissions data from this laboratory testing were used to determine the level of emissions per quantity of fuel consumed. Appendix B provides reference information for all of the data sources used in the study.

Table 4.2 Example of Bus Characteristics

Feature	Units	Fuel Cell Bus	Diesel Bus	Natural Gas Bus	Electric Trolley Bus
Make, model and year of sample bus		NEBUS	New Flyer Industries, D40LF, 1999	New Flyer Industries, C40LF, 1998	New Flyer Industries, D902, 1983
Range	km	N/D	750	650	N/A
Vehicle weight	kg	16,000	12,250	13,600	13,000
Passenger capacity	no.	70	77	61	76
Payload capacity	kg	N/D	17,200	4,400	17,532
Continuous power rating	kW	150	187	205	127
Est. lifespan	km	N/D	1,200,000	1,200,000	20 years
Vehicle length	m	12	12.2	12.2	12.2
Acceleration (0 to 30 kph)	sec.	N/D	7	8	8
Top speed	kph	N/D	110	110	65
Noise	dB	N/D	83	83	N/D

N/A – Not applicable N/D – No data available

4.2 System Process Flow Maps

For each system, a process map was developed to represent the life-cycle activities of the system. These maps show the cradle-to-grave life of the operation in a sequence of “Unit Processes.” Process maps are presented for the systems analyzed in Figures 4.2 through 4.17. The arrows connecting unit processes signify a flow of materials or energy. The boxes signifying manufacturing, maintenance and decommissioning phases of the life-cycle connect to each of the Unit Processes within the operation phase – indicating that each operation process has equipment or facilities that require manufacturing, maintenance and decommissioning. Some life-cycle activities, such as second-order fuel production (e.g., production of diesel fuel used to transport the primary fuel within the system) have been excluded from both the flow maps and the system modelling for the purpose of simplicity, and because they do not have a significant effect on the results.

The following is a list of general assumptions that apply to the hydrogen-based systems:
- The default is a gaseous hydrogen production and storage system, except for the scenario involving centralized hydrogen production that considers liquid hydrogen in a sensitivity analysis.
- Service stations with decentralized hydrogen production have the capacity to refuel 200 light-duty vehicles per day (based on 5 kg hydrogen per fill).
- Centralized steam methane reformers have the capacity to refuel 10,000 vehicles per day (based on 5 kg hydrogen per fill, 500 fills per station per day, and 20 stations per centralized reformer);
- Vehicle on-board storage of gaseous hydrogen occurs at 700 bar (10,000 psig). Refuelling stations store hydrogen at 825 bar (12,000 psig).[1]

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[1] Hydrogen storage pressures are currently only available at 350 bar (although Quantum Technologies has obtained 700 bar certification from TUV for operation in Germany); however, it was assumed that a pressure of 700 bar is needed for compressed hydrogen FCVs to have a range equivalent to gasoline vehicles. Therefore, by using the energy requirements to compress hydrogen to 825 bar, the results provide a more equivalent comparison.

Figure 4.2 System A – Internal Combustion Engine – Gasoline

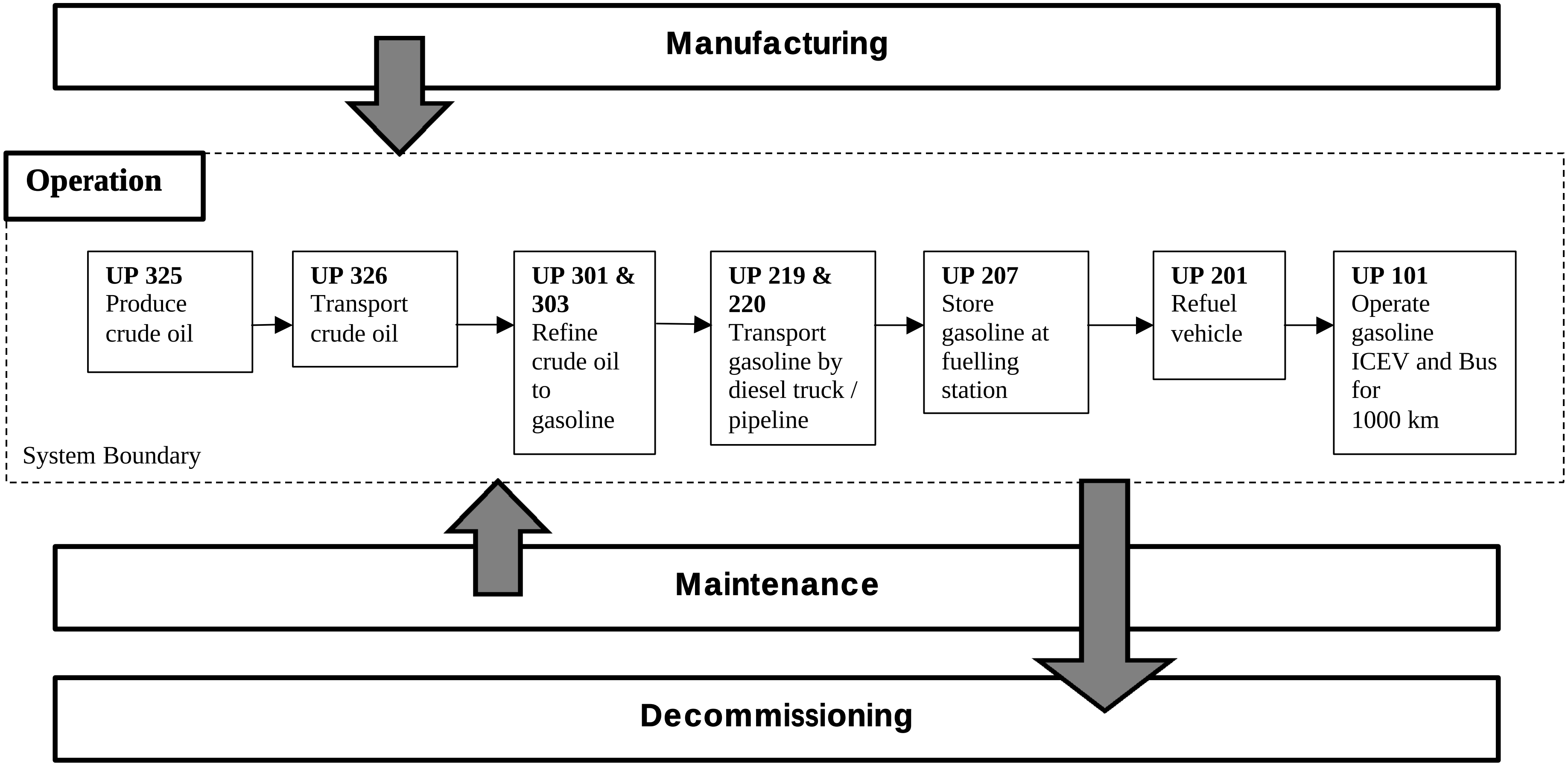


Figure 4.3 System B – Internal Combustion Engine – Diesel

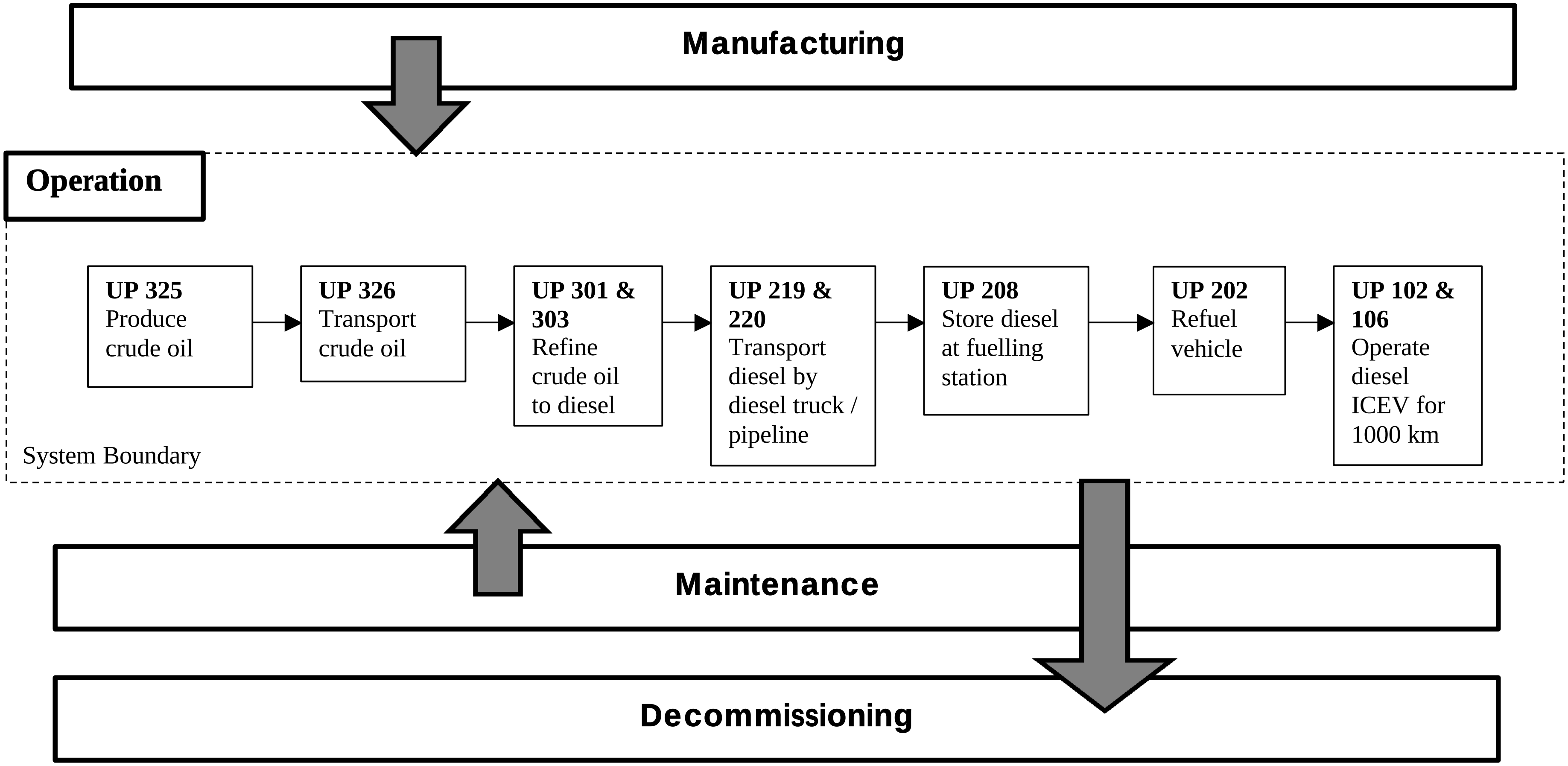


Figure 4.4 System C – Internal Combustion Engine Vehicle – Natural Gas

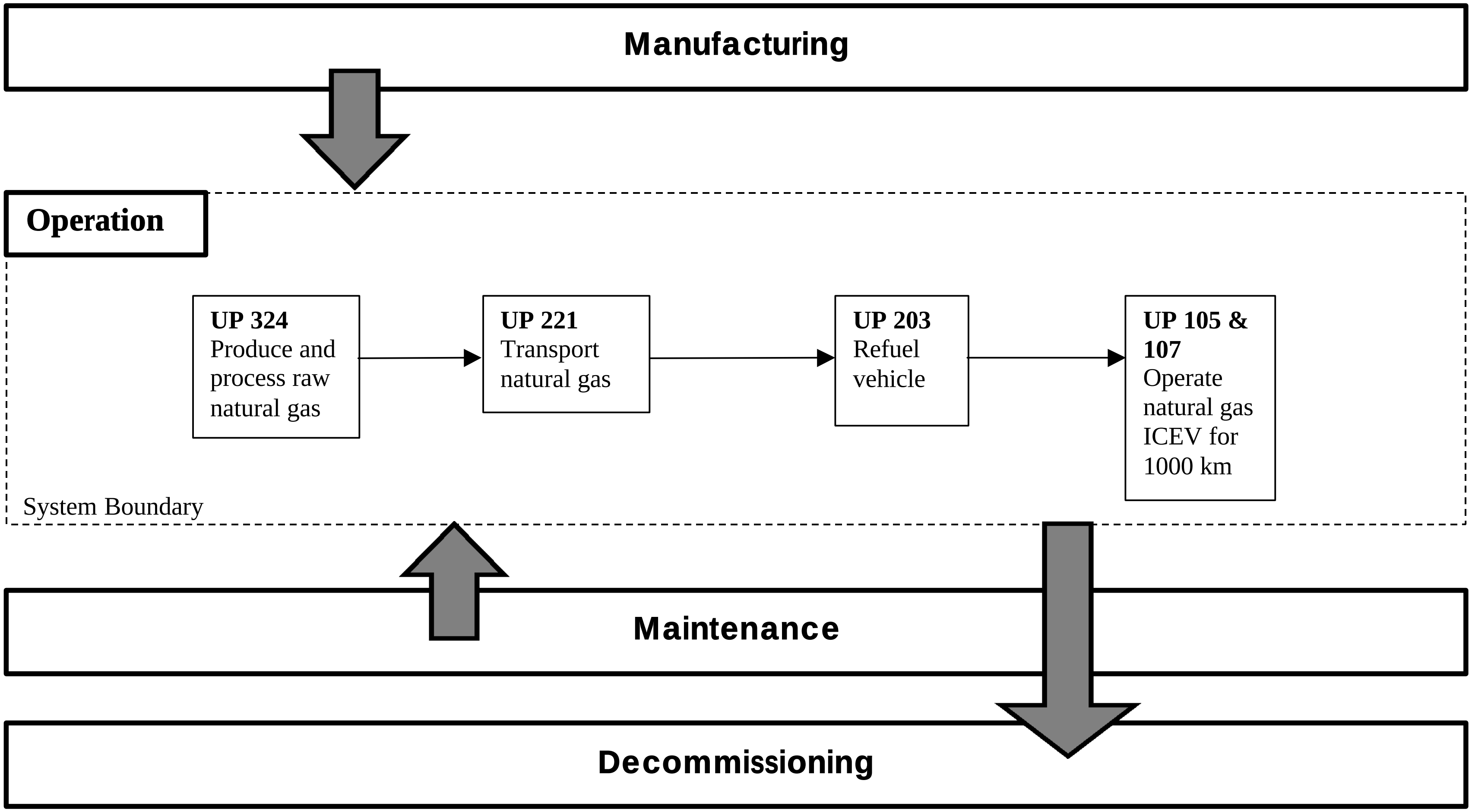


Figure 4.5 System D – On-Board Reforming of Methanol Produced from Natural Gas

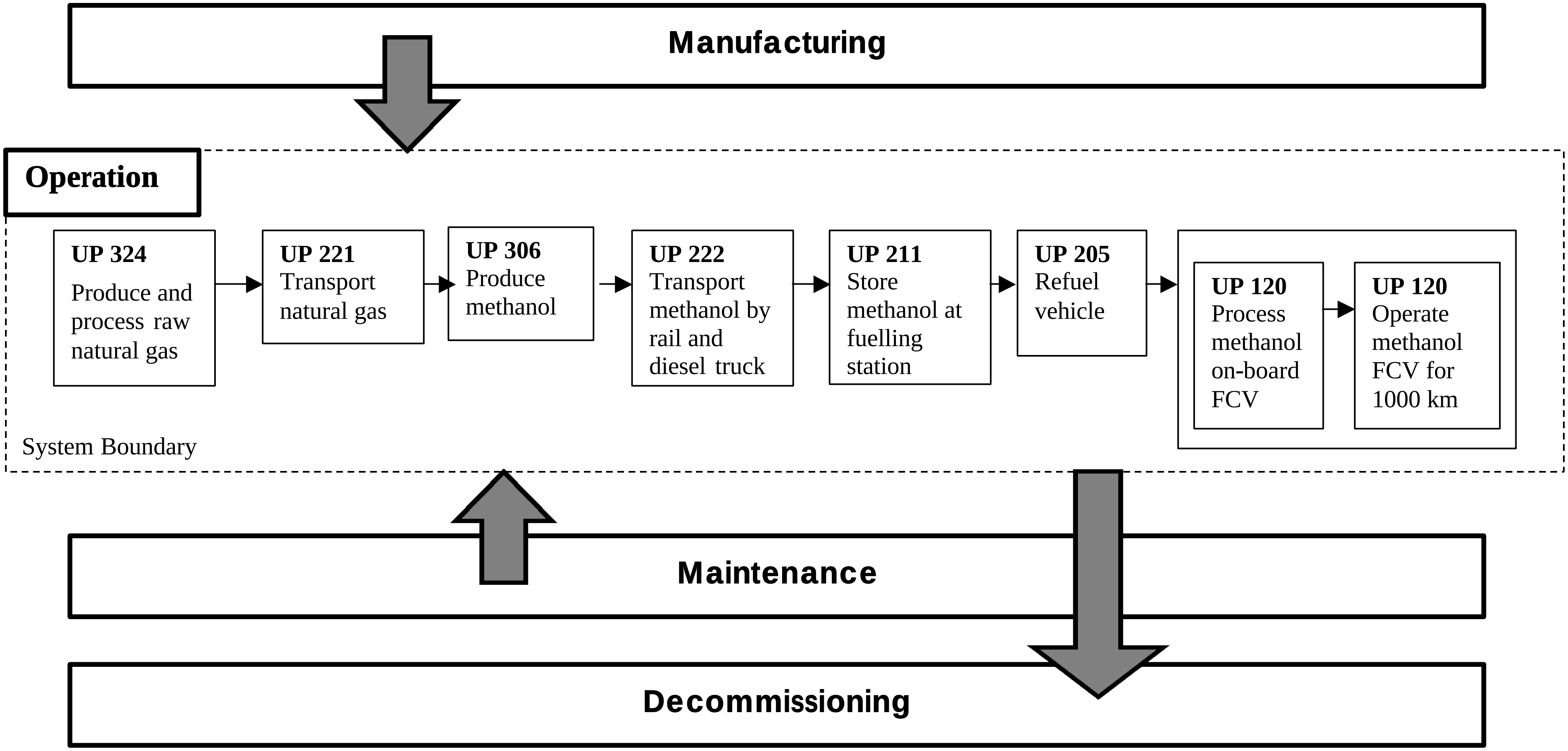


Figure 4.6 System E – Decentralized Reforming of Natural Gas

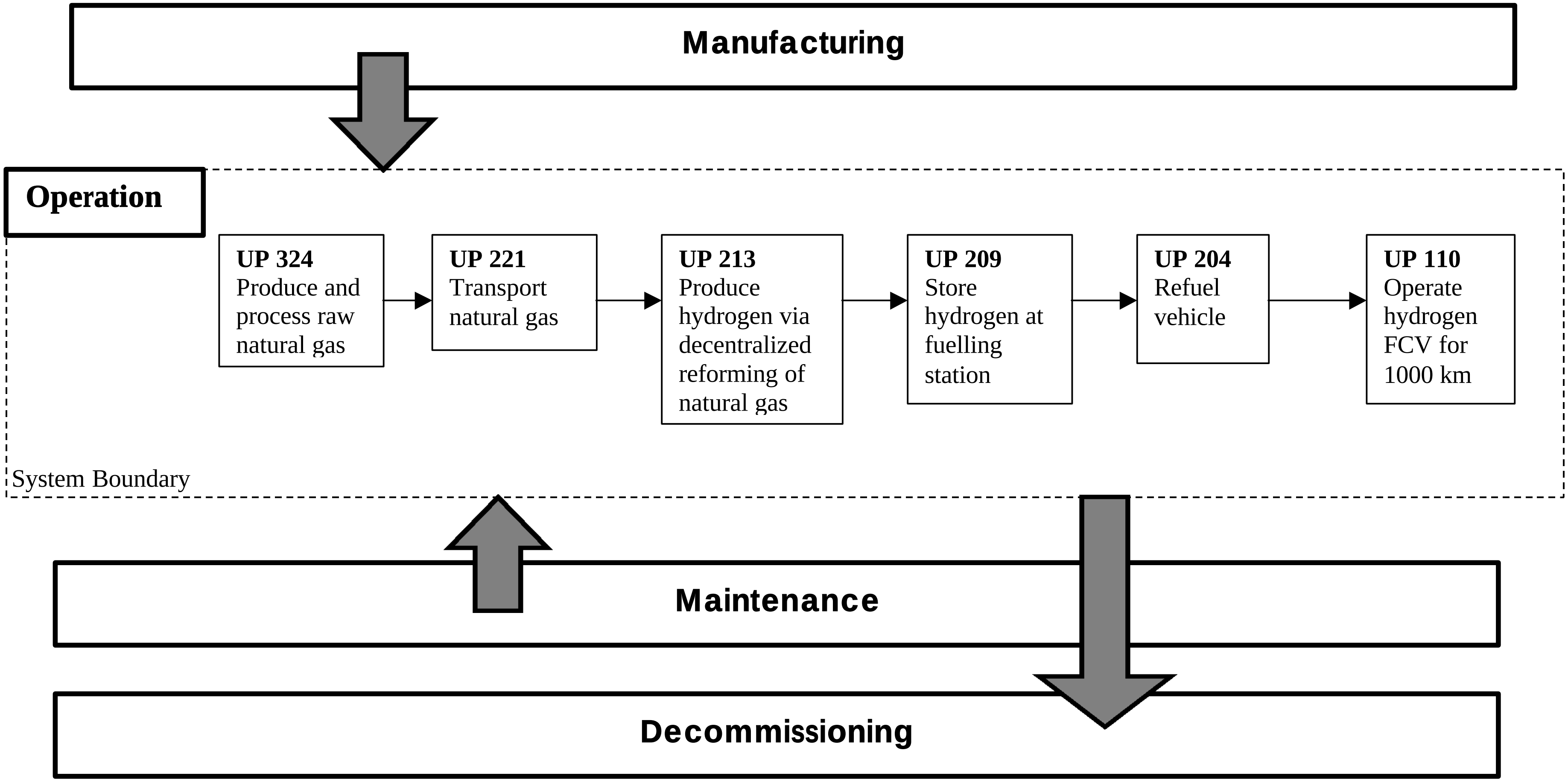


Figure 4.7 System F – Centralized Reforming of Natural Gas

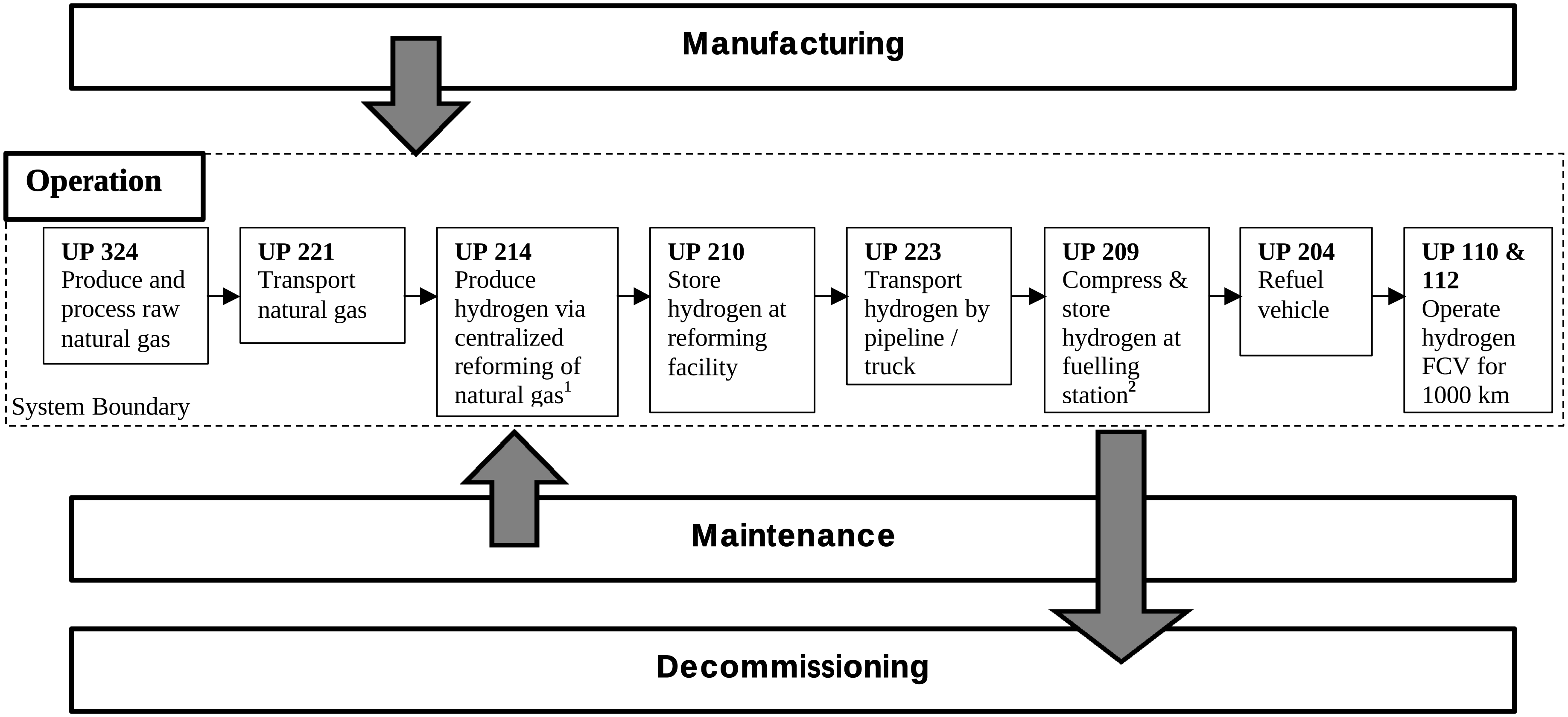


Figure 4.8 System G – Decentralized Electrolysis from Nuclear Power Plants

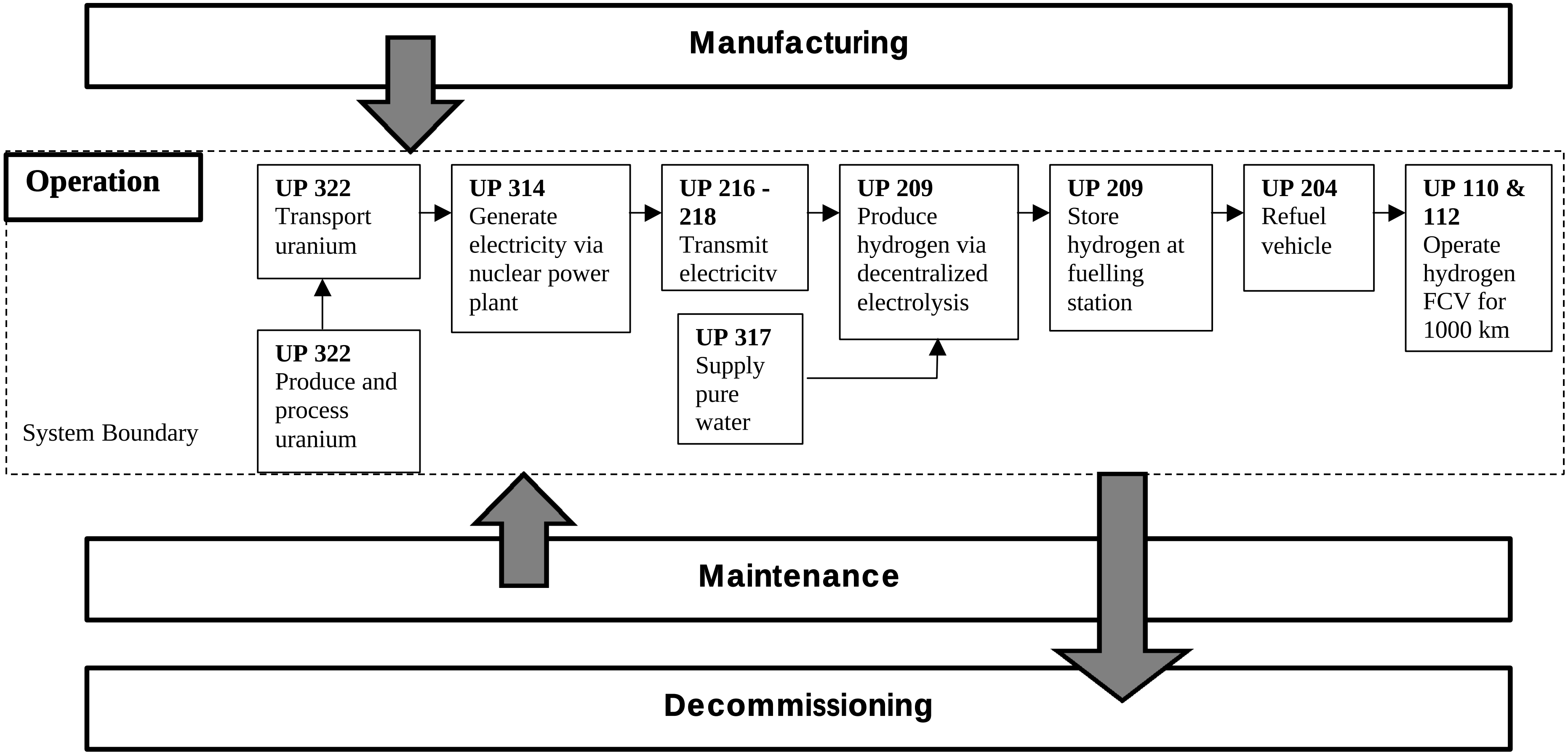


Figure 4.9 System H – Decentralized Electrolysis from Hydro Power Plants

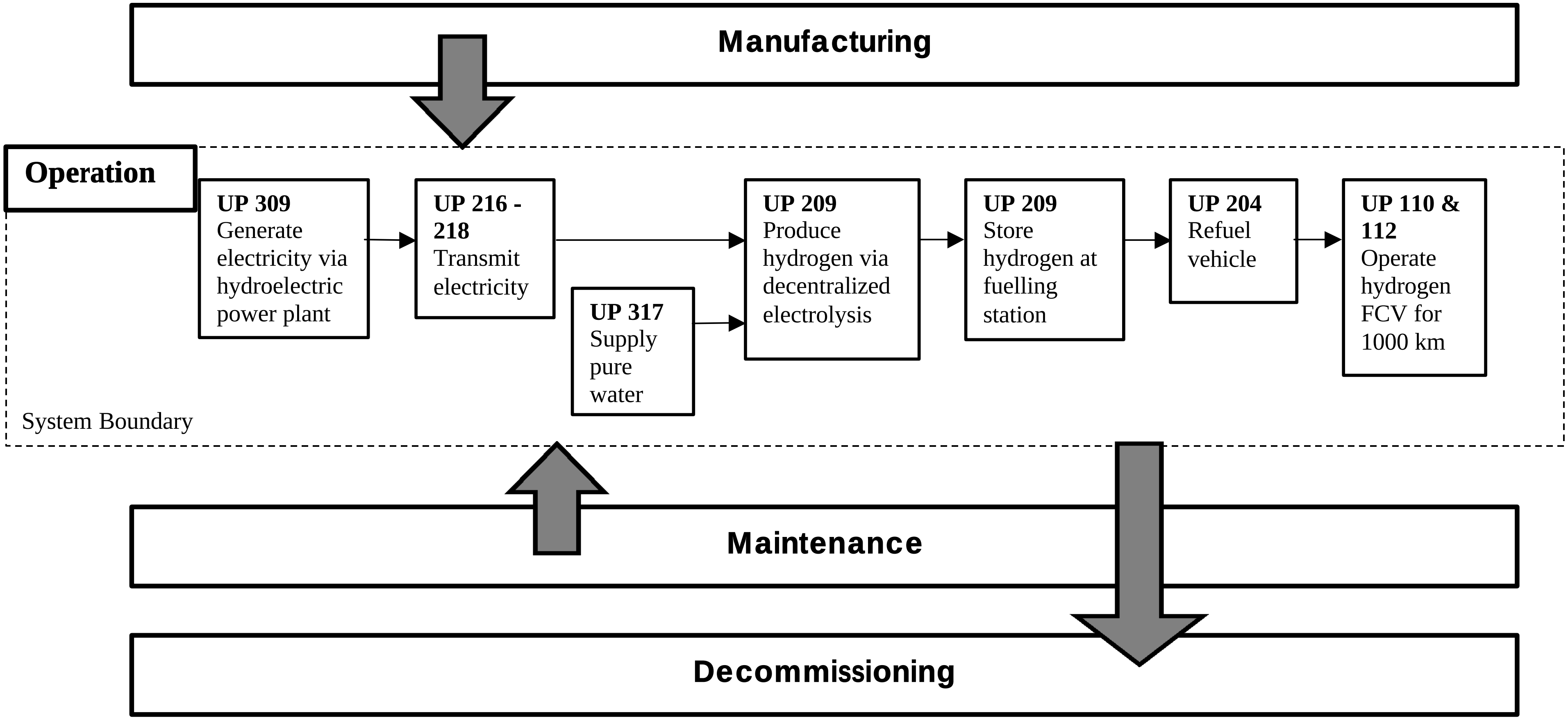


Figure 4.10 System I – Decentralized Electrolysis from Coal-Fired Power Plants

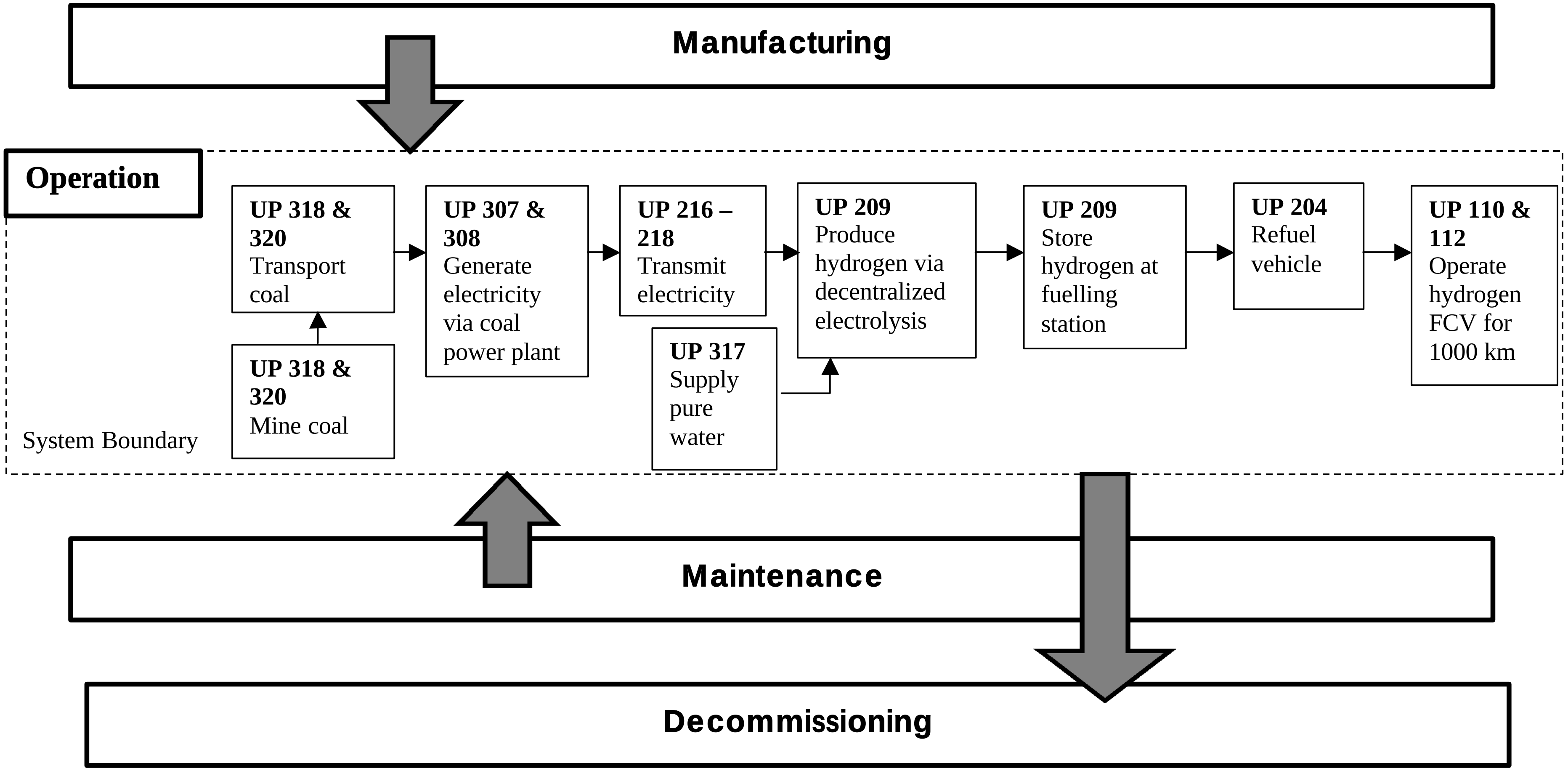


Figure 4.11 System J – Decentralized Electrolysis from Combined Cycle Gas Turbine (CCGT) Power Plants

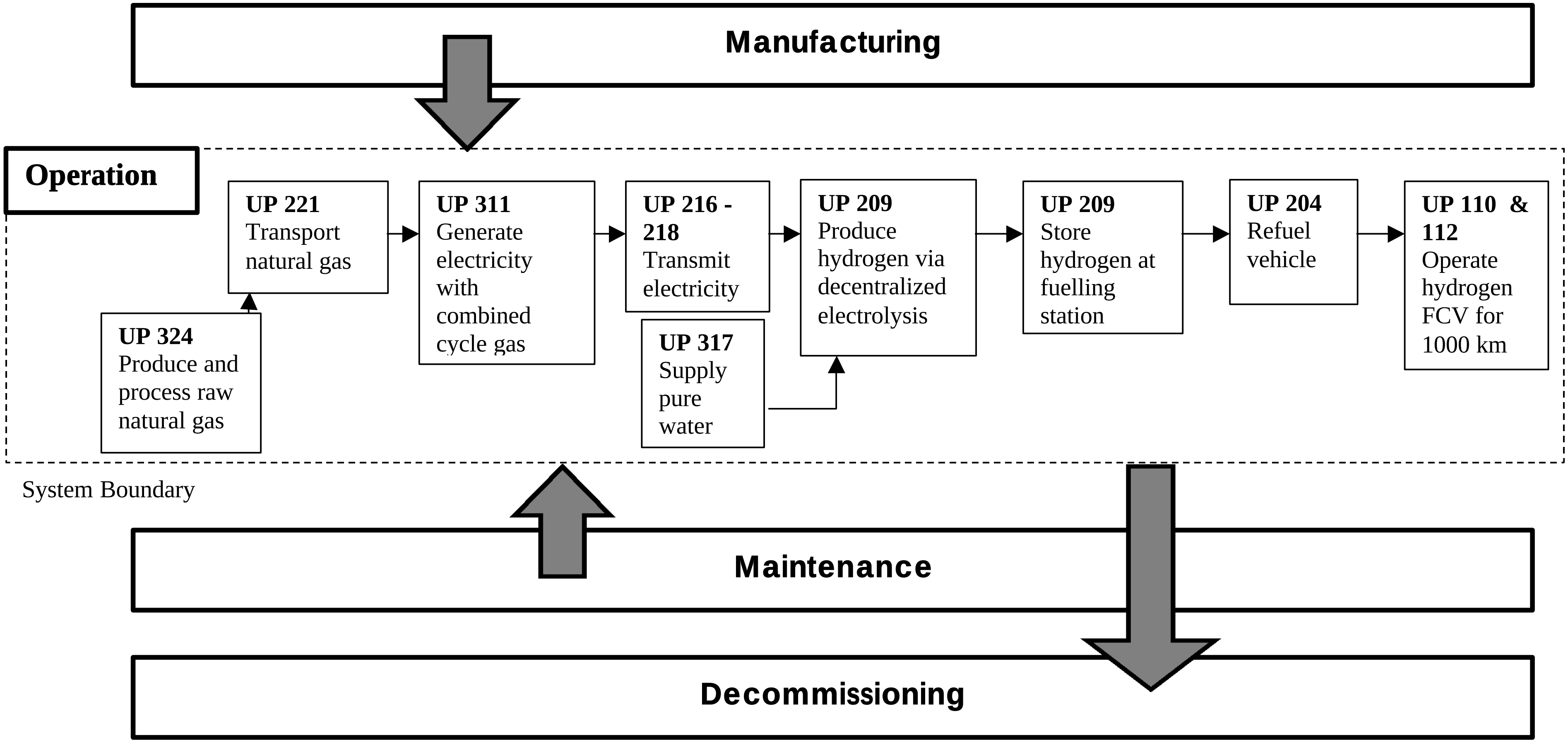


Figure 4.12 System K – Decentralized Electrolysis from Wind Power Plants

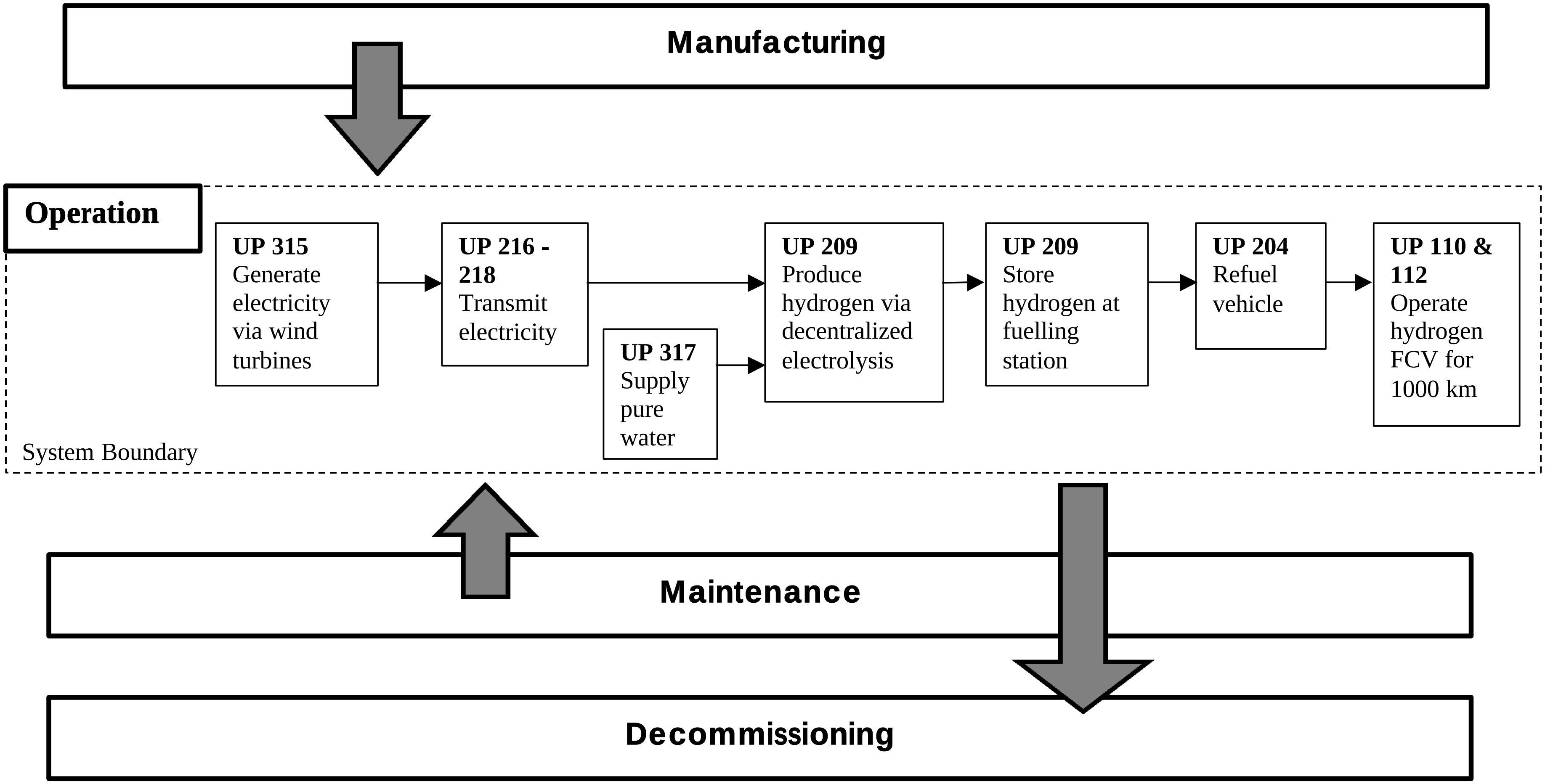


Figure 4.13 System L – Electric Vehicle – Electricity Produced from Nuclear Power Plants

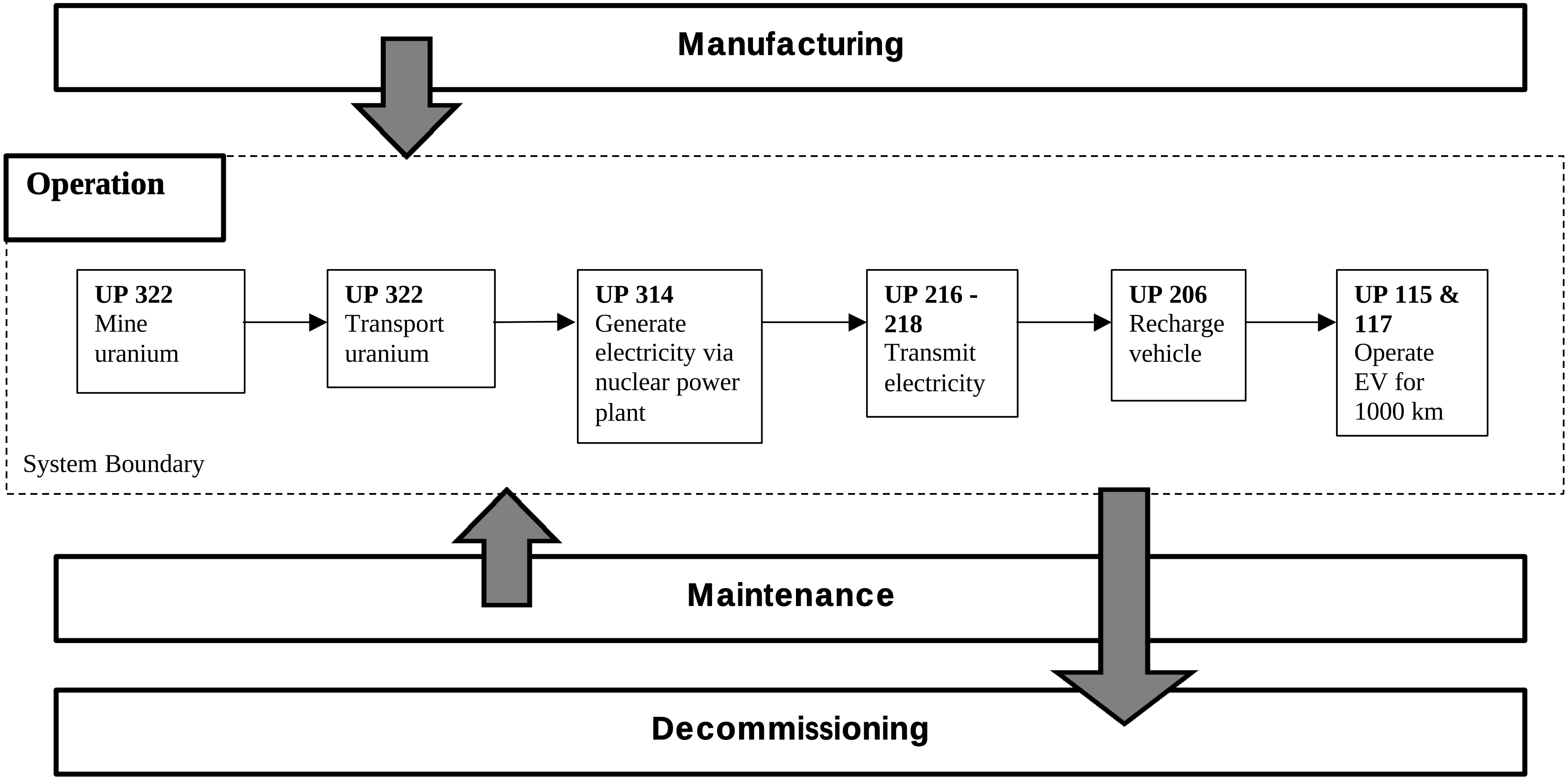


Figure 4.14 System M – Electric Vehicle – Electricity Produced from Hydro Power Plants

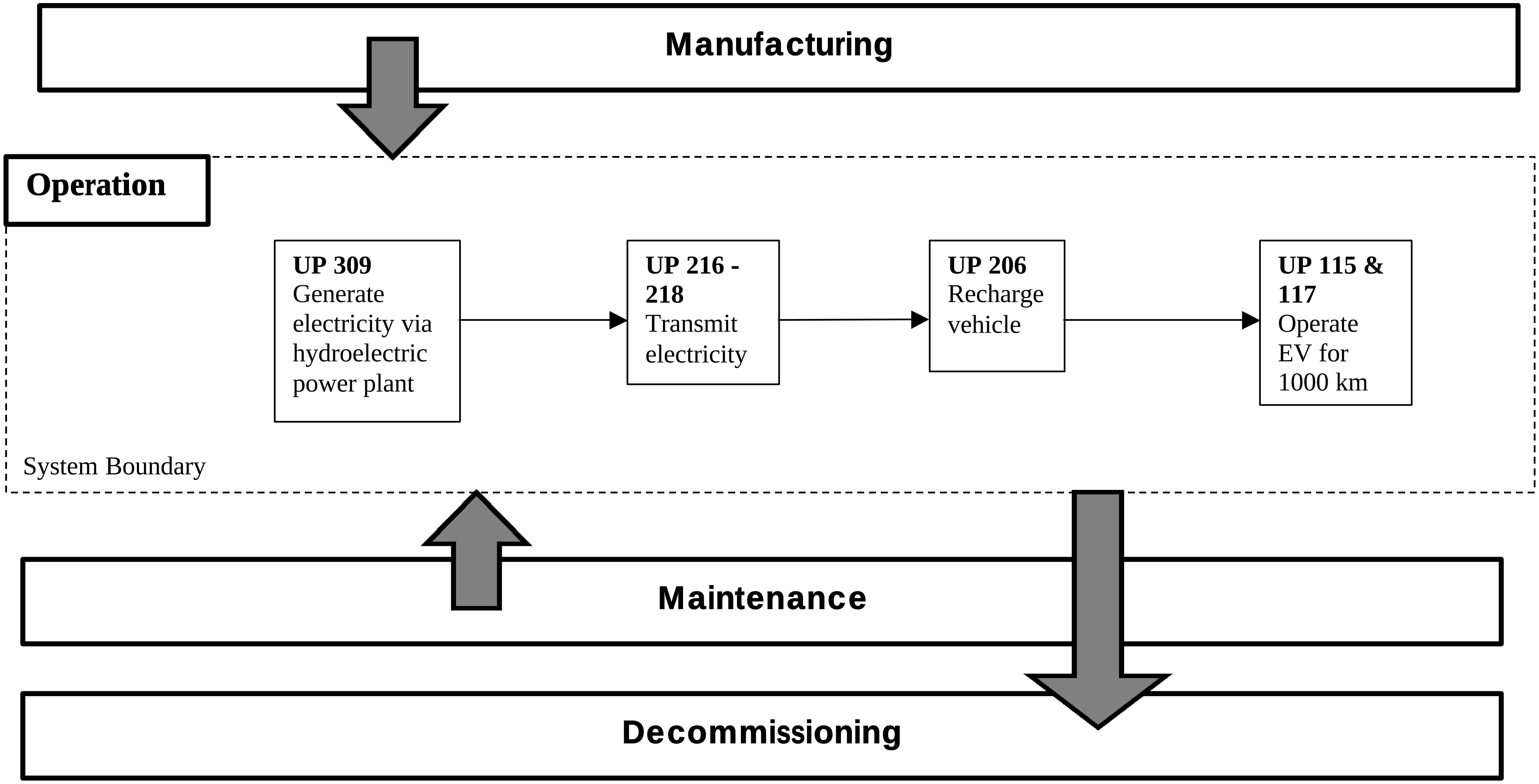


Figure 4.15 System N – Electric Vehicle Electricity Produced from Coal Fired Power Plants

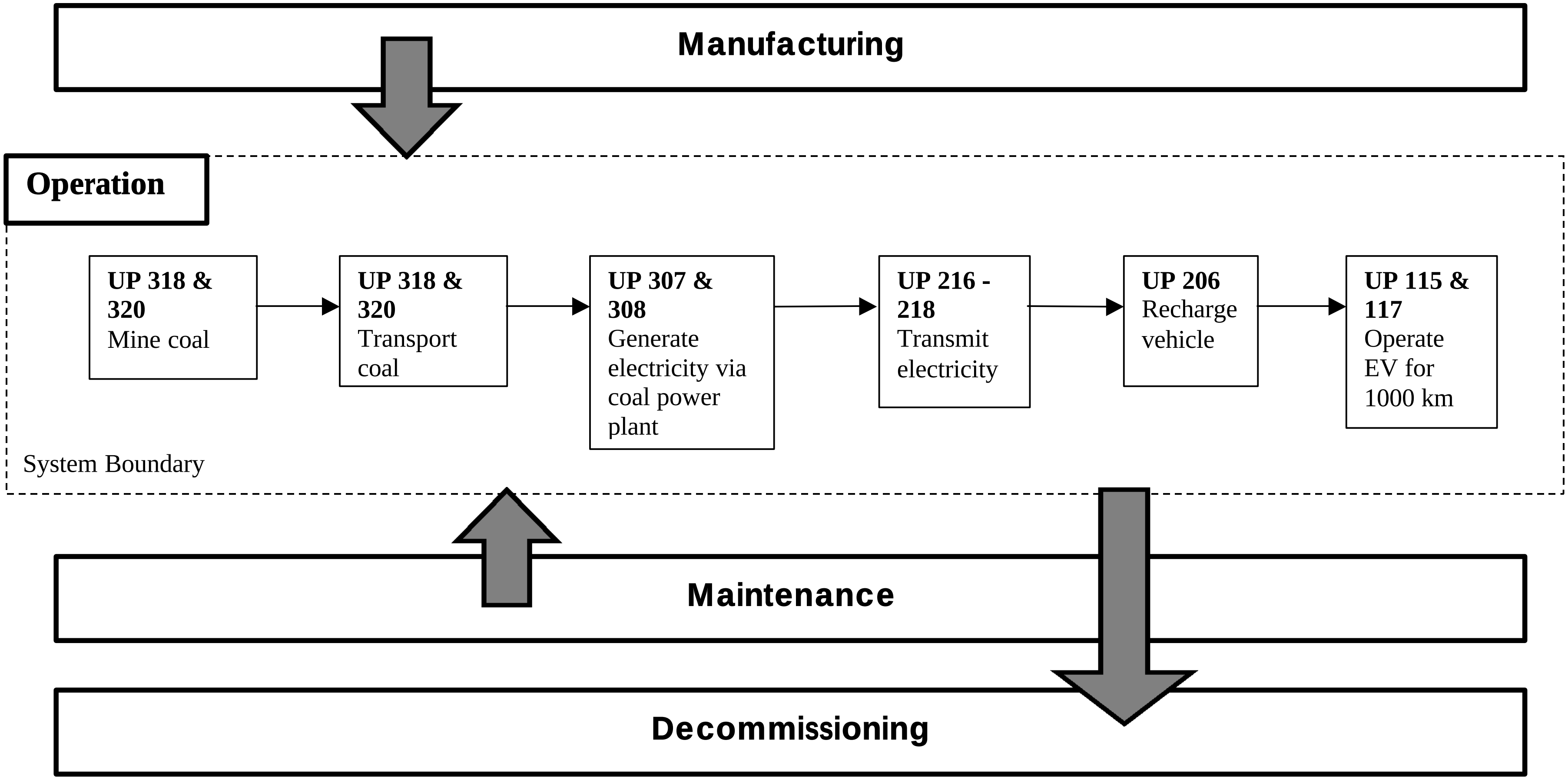


Figure 4.16 System O – Electric Vehicle – Electricity Produced from Combined Cycle Gas Turbine (CCGT) Power Plants

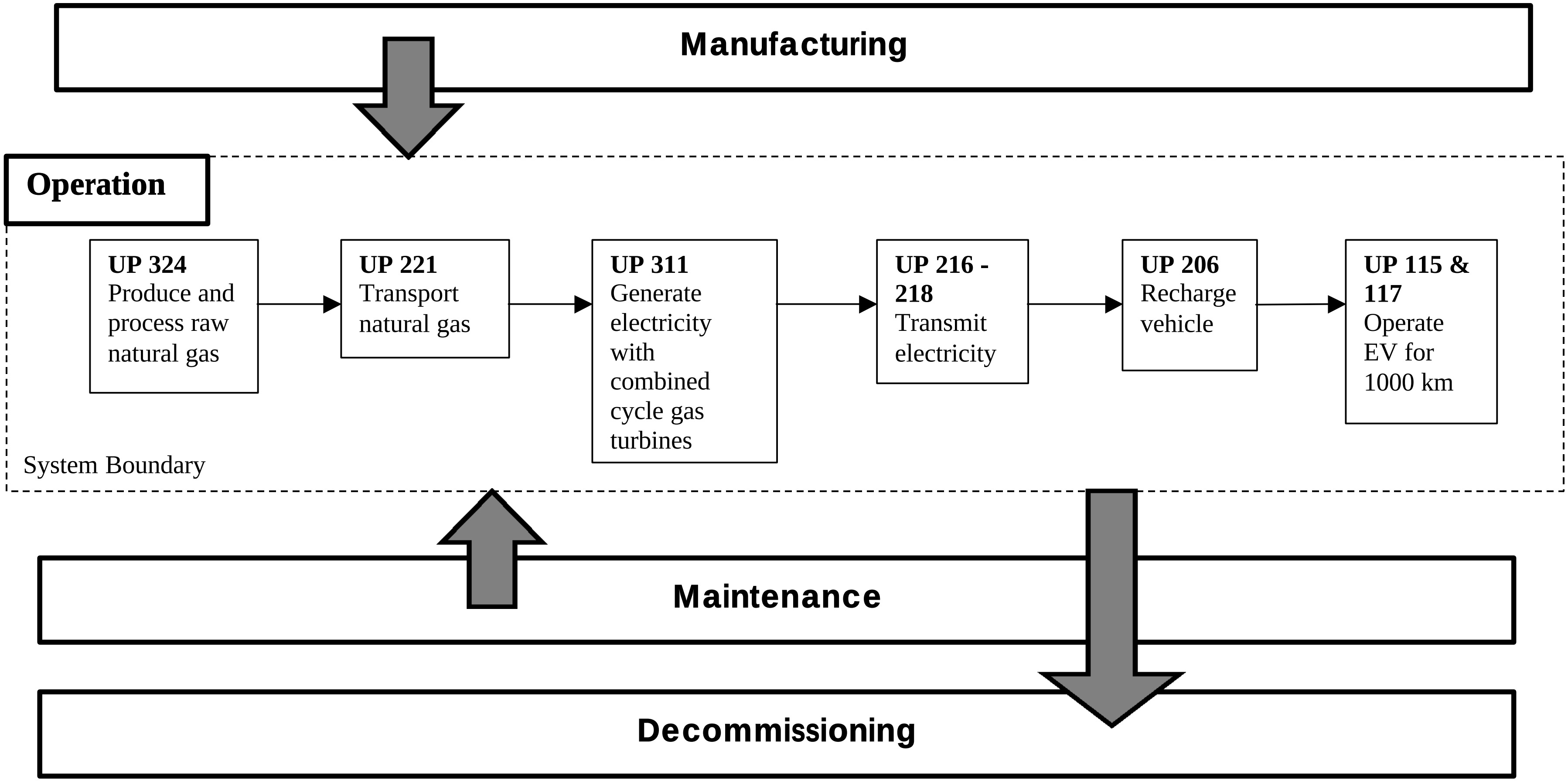
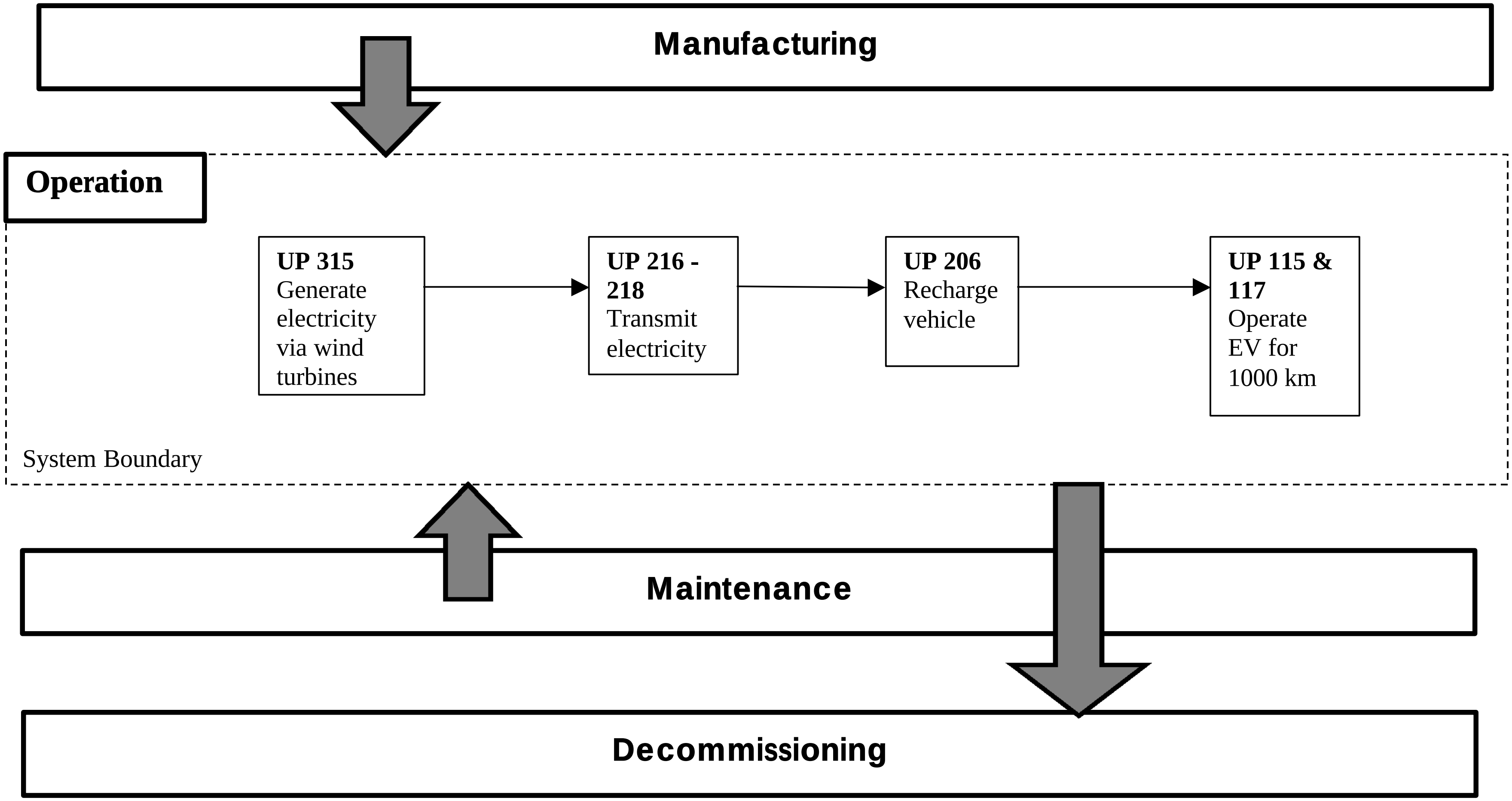


Figure 4.17 System P – Electric Vehicle – Electricity Produced from Wind Power Plants



4.3 Description of Scoping Process

The task of scoping each system to identify potential environmental, economic, technical and social issues was completed by members of the project team utilizing the Pembina Institute Unit Process scoping template. Each unique Unit Process was scanned individually and listings of the most significant issues were compiled for review by the technical steering committee. This process led to the establishment of the system boundaries and directed the level of research used to investigate each issue area. The environmental impacts have been split into two categories: those to be quantified on a life-cycle basis and those to be discussed qualitatively. The environmental impacts to be quantified are listed in Section 5.1, "Selection and Description of Environmental Stressor Categories," and include criteria air pollutants and greenhouse gas emissions. Further discussion of the results from the scoping process are located in Sections 6 to 8 – "Social Considerations," "Technical Considerations," and "Economic Considerations." A general description of each Unit Process that is within the system boundaries is located in Appendix B.

4.4 System Boundary Selection

Selecting a system boundary is a very important step in any LCVA. The objective is to minimize the number of unit processes that require intensive data collection while ensuring that a fair and thorough comparison is made. In general, three types of unit processes were placed outside of the system boundaries: product construction/production, maintenance, and decommissioning or disposal. The focus of the LCVA is therefore placed on the fuel production, distribution and consumption.

By not evaluating the effects of infrastructure and vehicle manufacturing, maintenance and disposal, the results of the LCVA will not reflect a complete life-cycle assessment of the systems investigated. However, the relative environmental impacts of these unit processes are expected to be small when considered over their lifetime as compared with the impacts of the daily operation of the system. Given that approximately 15% of the life-cycle environmental releases of a vehicle result from manufacturing and 85% from the use of the vehicle (Sullivan 1998), and the relative difference between the vehicles being evaluated is very small (e.g., the bodies, frame, wheels, interior and glass are all relatively equal in amounts between the vehicles), the overall environmental implications of the manufacturing of the vehicles plays a relatively small role in the life-cycle emissions when compared with the fuel production and use. This LCVA is therefore limited in the areas where manufacturing and disposal of the selected vehicles are significantly different, such as in the use of unique materials (e.g., batteries for EVs and HEVs). Ultimately, the results will show the potential environmental, economic and social impacts of the daily operation of light-duty vehicles and buses in three Canadian cities.

5 Environmental Considerations

When considering the environmental impact of vehicle / fuel supply systems, it is important to first identify which environmental factors are important to investigate and to what detail they should be evaluated. Next, it is important to determine the context or background within which environmental impacts occur. Different environmental stressors are considered at different levels of importance depending on the regional and individual circumstances of the parties affected. The actual quantification and analysis of impacts occurs in the inventory analysis.

5.1 Selection and Description of Environmental Stressor Categories

Environmental stressor categories are groups of individual environmental outputs that share a common type of potential impact on the environment. For example, “greenhouse gases” is an aggregate parameter comprising different emissions (e.g., carbon dioxide, methane, nitrous oxide, chlorofluorocarbons, etc.) that are weighted, if appropriate, and aggregated together. The use of these stressor categories allows the selected systems to be compared based on their relative potential impacts on the environment.

Based on the results from the scoping exercise, the identified environmental stressor categories were evaluated to determine the categories that were of primary importance to quantify and had a reasonable amount of data available given the resources available to the project team. Consequently, the quantification of environmental stressors has been limited to the following air-based stressor categories:

- greenhouse gases
- acid deposition precursors
- criteria air contaminants
    - ozone
    - particulate matter
    - sulphur dioxide
    - nitrogen oxides
    - carbon monoxide

The remaining environmental stressor categories that were not selected for quantification are discussed qualitatively in Section 5.6.

5.1.1 Background on Greenhouse Gases (GHG)

Emissions resulting from human activities, particularly the burning of fossil fuels, are substantially increasing the atmospheric concentrations of several important greenhouse gases, especially carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). These increases are enhancing the greenhouse effect, resulting in an overall average warming of the Earth’s surface. If emissions continue according to current trends, the temperature increase projected during the current century is expected to have a dramatic impact on the Earth's climate system, resulting in more extreme precipitation events over many areas and consequential flooding, increased risk of drought over most continental interiors, increasing rates of biodiversity loss, and especially rapid change in the Arctic. (IPCC 2001a,b)

The global warming potential of the various greenhouse gases is commonly presented in their equivalence to carbon dioxide to affect global warming (using the units “kg CO_2 eq”). The Intergovernmental Panel on Climate Change uses factors of 21 and 310 for the 100-year global warming potential of methane and nitrous oxide respectively.

Total greenhouse gas emissions in Canada in 1996 were 671 megatonnes (Mt) of CO_2 equivalents (CO_2 eq). Transportation accounts for approximately 26% of these emissions, which is the largest contribution from any single sector. Two other industry sectors that are a significant part of the systems being evaluated are the oil and gas sector, responsible for approximately 18% of national emissions (this includes the mining industry), and the electricity generation sector, responsible for approximately 15% of national GHG emissions (EC 1999).

Canada's commitment under the Kyoto Protocol is to achieve a 6% reduction in greenhouse gases from 1990 levels of 601 Mt CO_2 eq by 2010. The Action Plan 2000 on Climate Change, released in October of 2000, announced the federal government's intention to invest up to CAN$500 million over a five-year period in specific actions to reduce greenhouse gases. The most recent official national projection of GHG emissions in 2010 is 764 Mt CO_2 eq, 27% above 1990 levels (NRCan web site 1999).

5.1.2 Background on Acid Deposition Precursors (ADPs)

Acid deposition, which commonly occurs in the form of acid rain, is responsible for widely documented damage to lakes, forests, crops and buildings. As lakes become more acidic, plankton and invertebrates are the first to die, while over 75% of fish species cannot survive when the pH drops below 5. This affects not only life within the lakes, but also all life that relies on the lakes for survival. Trees are also unable to receive the nutrients that they require and are left susceptible to stunted growth, loss of leaves, climatic changes, diseases and pests. Acid deposition is more prevalent in eastern Canada where forests receive approximately twice the amount of acid that they are able to handle without long-term damage. Even with decreasing emissions of ADP, it is estimated that once 2010 targets are met, up to one-quarter of the lakes in eastern Canada will remain chemically damaged (EC web site 2002). The two key emissions associated with acid deposition are sulphur dioxide (SO_2) and nitrogen oxides (NO_X), while ammonia (NH_3) also contributes to its formation. The acidification potential of NO_X is 0.696 times that of SO_2, while ammonia is 1.9 times more potent on a mass basis – commonly presented as "kg SO_2 eq."

5.1.3 Background on Ground-Level Ozone Precursors (GLOP)

Elevated levels of ground-level ozone have been shown to cause adverse effects on humans, including irritation of the nose, throat and lungs; lowered lung function; and the development of chronic respiratory diseases possibly leading to increased respiratory hospital admissions and exacerbation of asthma (WHO 2000). Ground-level ozone has also been found to have significant impact on reducing the productivity of agricultural crops and forests (EC web site 2002). It is also a major constituent of smog. Nitrogen oxides (NO_X) and volatile organic compounds (VOCs) are key precursors to the production of ground-level ozone. While both NO_X and VOCs must be present for the creation of ground-level ozone, the relationship between ground-level ozone and its precursors involves a very complex process. The scale of environmental impacts from these precursors is regional. Depending on weather conditions, ozone precursors can travel hundreds of kilometres, or the constituents can concentrate in the local air shed if low wind conditions persist. Representing the quantities and concentrations of these precursors provides only a rough proxy for the actual environmental impacts of ground-level ozone.

Volatile organic compounds are made up of many different compounds, each with unique environmental and health impacts. The impacts of VOCs beyond the creation of ground-level ozone are discussed in Section 5.6.1, "Other Air Pollutants."

In 1995, the transportation sector and the oil and gas sector each accounted for 21% of total VOC emissions in Canada, while the electricity generation industry amounted to less than 1%. Through the Canadian Council of Ministers of the Environment NO_X/VOC Management Plan, Canada has set targets to reduce emissions of NO_X by 10% and VOCs by 15% by the year 2005, based on 1985 levels (CCME 1999).

5.1.4 Background on Particulate Matter (PM) and Secondary Particulate Matter Precursors (SPMPs)

Particulate matter (PM) consists of tiny pieces of solid and liquid matter small enough to be suspended in the air (also referred to as suspended particulate matter – SPM). Of special concern are PM_{10} and $PM_{2.5}$ – particulates smaller than 10 and 2.5 microns in size that can penetrate deeply into the lungs. $PM_{2.5}$ are considered fine particulates formed primarily during combustion or industrial processes and through secondary particulate formation in the atmosphere, while particles between 2.5 and 10 microns are formed primarily during construction and mining activities, and from disturbances on unpaved roads and soil erosion. Total suspended particulate (TSP) refers to all airborne solid and liquid particles ranging from 0.005 μm to 100 μm in diameter. Secondary sources of PM result from SO_2, NO_X, VOCs and ammonia emissions, which act as precursors to PM formation in the atmosphere. Secondary particulate matter precursors are aggregated into the SPMP stressor category. Limited studies of the Lower Fraser Valley in British Columbia indicate that as much as 50% of $PM_{2.5}$ may come from secondary sources during the summer months (Health Canada 1998).

For the purpose of quantifying particulate matter emissions in each scenario, the TSP emitted from each unit process has been quantified. Where possible, the size of PM emissions has been addressed. Precursors for secondary PM formation are quantified as a separate stressor category and are presented separately from primary PM emissions.

Human health effects of particulate matter include "acute effects such as increased daily mortality, increased rates of hospital admissions for exacerbation of respiratory disease, fluctuations in the prevalence of bronchiodilator use, cough and peak flow reductions. Long-term effects of SPM refer also to mortality and respiratory morbidity, but only a few studies on the long-term effects of SPM exist. Air pollution by particulate matter has been considered to be primarily an urban phenomenon, but in many areas of developed countries, urban-rural differences in PM10 are small or even absent, indicating that PM exposure is widespread. This is not to imply that exposure to primary, combustion-related PM may not be higher in urban areas." (WHO 2000) These particulates have also been linked to cancer, especially those particulates from diesel exhaust that contains carcinogenic fuel combustion products. In general, the finer the particles the more hazardous they are to human health, as they are able to penetrate deeper into the lungs and can contain higher levels of acids, heavy metals, and other organic compounds. Evidence has shown that there is no defined threshold level where particulate matter will have no adverse effects on humans (Health Canada 1998). In addition, PM is being considered under the CEPA Priority Substances List II process for inclusion in the list of air toxics (EC web site 2002).

Particulates also impact the vegetation, structures and aesthetics of a region. They have a negative impact on plant growth and productivity by interfering with photosynthesis and, depending on particle composition, delivering toxins to the plant. Particulate deposition on materials can impact their aesthetics and increase their physical and chemical breakdown. Fine particles can also have an impact on the aesthetics of an entire region by limiting visibility and giving the perception of poor air quality.

Utilizing National Air Pollution Surveillance monitoring network data, the highest PM_{10} concentrations over a 24-hour period were measured in Montreal, Windsor, Hamilton, Walpole Island and a single site in Calgary, and $PM_{2.5}$ concentrations were highest in Montreal, Toronto, Hamilton, Windsor, Walpole Island and Vancouver. Hebdomadal (day of the week) variations in PM_{10} and $PM_{2.5}$ concentrations suggest that transportation is a substantial emission source. Near roadways, as much as a 50% increase in PM_{10} and up to a 60% increase in $PM_{2.5}$ emissions has occurred in the middle of the week as compared with Sundays. (Health Canada 1998)

5.1.5 Background on Sulphur Dioxide (SO_2)

In addition to being an acid deposition and a particulate matter precursor, sulphur dioxide inhibits respiratory function by causing breathing discomfort, respiratory illness and cardiovascular disease. SO_2 particularly affects those with asthma, bronchitis or emphysema, as well as children and the elderly. SO_2 is produced by the combustion of fossil fuels containing sulphur. The main sources of sulphur oxides in Canada are smelters (34%) and power plants (20%), although upstream oil and gas, oilsands and refinery operations combined for approximately 26% of the national total – based on the 1995 Environment Canada Emission Inventory (EC web site 2002). Transportation sources accounted for 5% of the total SO_X emissions.

5.1.6 Background on Nitrogen Oxides (NO_X)

In addition to being an acid deposition precursor, ozone precursor and a particulate matter precursor, nitrogen dioxide (a major component of NO_X) decreases pulmonary function, irritates the lungs, facilitates bronchitis and pneumonia, and lowers resistance to respiratory infections and disease. Once again, there is an increasing sensitivity for those with asthma and bronchitis. NO_X are by-products formed from the combustion of fossil fuels. In Canada, the primary source of NO_X is the transportation sector (52% in 1995), with oil and gas–related industries accounting for 15% of national emissions and electricity generation contributing 10%.

5.1.7 Background on Carbon Monoxide (CO)

Carbon monoxide is a colourless, odorless and poisonous gas produced through incomplete combustion of carbon in fuels. When CO enters the bloodstream, it reduces the delivery of oxygen to the body's organs and tissues, beginning with organs and tissues of high oxygen consumption, such as the brain, heart, exercising skeletal muscle and a developing fetus. Exposure to elevated CO levels can cause impairment of visual perception, manual dexterity, learning ability and performance of complex tasks. “Severe hypoxia due to acute CO poisoning may cause both reversible, short-lasting, neurological deficits and severe, often delayed, neurological damage.” (WHO 2000) Health threats are most serious for those who suffer from cardiovascular disease, particularly those with angina or peripheral vascular disease. Transportation sources accounted for 65% of anthropogenic carbon monoxide emissions in 1995.

5.2 Regional Context of Quantitative Stressor Categories

When analyzing the environmental impact of a system, it is important to consider the location at which the pollution occurs and the area that will be impacted by such emissions. Most of the above stressor categories, with the exception of GHG emissions, which impact the global environment, and carbon monoxide, which is relatively short-lived, have regional impacts that may occur as much as several hundred kilometres away from the source. Consequently, it is necessary to define the various regions where the life-cycle emissions of each scenario take place. A brief description regarding regional air quality issues is also included. This is by no means a complete evaluation of the air quality issues of the region and is presented simply for the purpose of providing some context around environmental impacts and pollutant levels that have been identified by other parties. All of the information presented was obtained through public sources. Figure 3.2 shows the location of each region within Canada.

5.2.1 Lower Fraser Valley

The city of Vancouver is located in the region known as the Lower Fraser Valley – a densely populated area of southwestern British Columbia that stretches from Bowen Island to Hope. The entire Lower Fraser Valley (LFV) region shares the management of air quality within the region, although most of the management is focused on the Greater Vancouver Regional District (GVRD). The GVRD operates one of the most extensive ambient air quality monitoring networks of any urban area in North America: it consists of 27 permanent air quality stations for the entire Lower Fraser Valley. In the year 2000, the Air

Quality Index was in the "Good[2]" range for 98.4% of the time (GVRD & FVRD 2001). Given the constrained air shed of the Lower Fraser Valley and the growth in population in the area, minimizing air pollutants from the combustion of fossil fuels is important to maintaining a high standard of air quality. Emissions occurring from vehicle operation, fuel production and transportation, and natural gas electricity generation within Vancouver were allocated to the Lower Fraser Valley region.

5.2.2 Calgary

The Calgary region includes the city of Calgary and its surrounding agricultural land. Air quality is measured on a continuous basis at three stations in Calgary: Northwest, Central and East locations. For the year 1996, the national 24-hour guideline for ozone was exceeded 23, 144, and 63 times at each of the stations. Levels of particulate matter were also exceeded during the year for both the 24-hour provincial guideline (on 3 occasions at Calgary Central and 18 times at Calgary East), and the annual average, at Calgary East. For carbon monoxide, the 1-hour guideline was exceeded twice at the Calgary Central location in 1996, and the Calgary East and Central sites both exceeded the 8-hour guideline four times in 1996. The CO exceedances were likely caused by vehicle exhaust with strong temperature inversions and strong winds. In general, Calgary and Edmonton both show levels of NO_2, SO_2 and CO that are higher than the rest of the province (AB Env 2001). Given the high rate of growth and expansion of Calgary, the increased use of personal vehicles running on gasoline has a significant potential to negatively impact the local air quality of the city.

Emissions occurring from vehicle operation, fuel production and transportation within Calgary will be allocated to the Calgary region. The electricity generation that occurs near the city has been allocated to the region defined as "Alberta," indicating that electricity generation takes place throughout the province and affects many regions. A breakdown of the electricity generation emissions for each region within the province was not completed.

5.2.3 Windsor–Quebec City

The Windsor-Quebec City region is an area of Southern Ontario and Quebec that shares many air quality concerns, and the various governments that are included in this region work co-operatively on many air quality issues. This region stretches from Windsor, Ontario, to Quebec City, Quebec, and includes the city of Toronto along with many oil refineries and power plants that supply Southern Ontario with energy. Acid deposition is an issue that is of concern particularly for this region. The Canada-Wide Acid Rain Strategy for Post-2000 indicates that both SO_2 and NO_X emissions in eastern Canada and the United States will require further reductions. The New England Governors / Eastern Canadian Premiers Acid Rain Action Plan has set targets for SO_2 national emission reductions of at least 50% by 2010, beyond the current international commitment that caps SO_2 emissions at 3,200 kt by 2000. NO_X emission reduction targets for 2007 are set at 20%-30% beyond the current commitment of a 100 kt reduction by 2000.

If we view air quality in the city of Toronto as an indicator for the region's air quality concerns, it is apparent that levels of all common air pollutants are of public health concern. Toronto recorded the highest composite annual mean for NO_2 in 1999 among major cities in Canada, as well as the highest average from 1990 to 1999. In 1996, Toronto's yearly average exceeded the national desirable criteria. According to Reuters News Service, in 2001 Ontario Power Generation (OPG) is investing significant amounts of money at two coal-fired generating stations to reduce nitrogen oxide emissions – resulting in a reduction of provincial emissions by approximately 2% and indicating a considerable concern for NO_X emissions in the region.

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[2] Defined as below the maximum desirable level-based on federal objectives.

Ozone levels often exceed the Ontario ambient air quality criteria. In 1999, out of seven major cities in Canada, Toronto ranked second for the highest one-hour maximum for ozone and exceeded the Ontario criteria by 40%. Over a ten-year period, from 1990 to 1999, Toronto recorded the highest one-hour ozone concentrations out of seven major cities across Canada. A major contributing factor to these high levels is the long-range transport of ozone precursors from the mid-western states in the United States via the Windsor–Quebec City corridor. The year 1996 was an extremely bad year, with exceedances measured 48 times. It is difficult to predict the long-term trends for ozone, as levels are strongly influenced by the weather; however, Environment Canada has shown a yearly rise in average ozone levels in Toronto based on data adjusted for temperature.

Concerning particulate matter, in 1996 the maximum 24-hour level of TSP exceeded the provincial acceptable guideline by over 100%. In the same year this guideline was exceeded a total of nine times at one particular location. It has also been noted that “sites in Ontario seem to exhibit daily summertime maximum PM_{10} concentration, which may reflect the greater abundance of secondary aerosols in the Windsor–Quebec City Corridor, where precursor concentrations are known to be high.” (Health Canada 1998)

Another indicator of poor air quality is the fact that in Toronto the number of smog alert days increased from 1 day to 9 days from 1993 to 1999 in a generally upward trend. The City uses a smog alert to warn citizens of particularly high levels of air pollutants. The summer of 2001 saw particularly warm weather and an increase to 23 smog alert days.

Concerning carbon monoxide, “calculations done by Toronto Public Health using 1995 data showed that at daily average concentrations of 0.5 to 1 ppm, carbon monoxide could be responsible for about 33 per cent of early-deaths due to air pollution. It was also linked to 5 per cent of pollution-related hospital admissions for heart problems.” (Toronto Public Health 2000) However, there is some debate surrounding the Toronto Public Health study conclusions due to the fact that some other air pollutants, such as PM, may not have been properly accounted for.

5.2.4 Edmonton

The activities allocated to the Edmonton region include all refinery emissions for both the Calgary and Vancouver scenarios. Air quality is measured on a continuous basis at three stations in Edmonton (Northwest, Central and East locations), as well as in Fort Saskatchewan, which is slightly northeast of Edmonton and is home to a large refinery. For the year 1996, Alberta Environment reported that the national 24-hour guideline for ozone was exceeded 119 and 181 times at the Edmonton East and Fort Saskatchewan locations respectively. Levels of total suspended particulate, based on the 24-hour provincial guideline, were also exceeded during the year (on 7 occasions at Edmonton Central, 3 times at Edmonton East, and once in Edmonton Northwest and Fort Saskatchewan). For carbon monoxide, the 8-hour guideline was exceeded twice at the Edmonton Northwest location in 1996. Total hydrocarbons measured in Edmonton East peaked at a level 3 times higher than was measured elsewhere in the province. Alberta Environment states that these high hourly values are likely due to fugitive emissions from petroleum transport vehicles, storage tanks and processing plants (AB Env 1998). In general, Calgary and Edmonton both show levels of NO_2, SO_2 and CO that are higher than the rest of the province, and Edmonton’s surrounding area also shows high values of PM (AB Env 2001).

5.2.5 British Columbia

For the purposes of this study, the British Columbia region accounts for all emissions created from the transportation of hydrocarbons via pipeline or rail from the areas of fuel production (typically in Alberta) to Vancouver. The majority of these emissions represent a small amount of the total life-cycle emissions and take place in areas of relatively low population density. Therefore, the specific local environmental issues of the British Columbia region will not be discussed.

5.2.6 Alberta

For the purposes of this study, the Alberta region accounts for all emissions created from the generation of electricity (including coal mining) and transportation of hydrocarbons for the Calgary scenarios. Passive monitoring by Alberta Environment shows:

- higher levels of ozone in the West Central Air Shed zone;
- high levels of PM near Edmonton; and
- "strikingly" high levels of SO_2 in Mannix and Mildred Lake, where extensive development of the Athabasca oilsands has taken place and continues to expand. (AB Env 2001)

5.2.7 Alberta to Southern Ontario

The emissions from the pipeline and rail transport of hydrocarbons from the area of production to the area of use occur in the Alberta to Southern Ontario region. As in the British Columbia region, the emissions allocated to this region are smaller than for other regions and they are spread out over a very large area; therefore, the specific local issues regarding this region will not be discussed.

5.2.8 Oil and Gas Production

The region of oil and gas production has been separated from other regions because it is an industry with a specific set of air quality concerns that are spread over a wide area and many geographical regions. The majority of oil and gas production in Canada occurs in the province of Alberta (approx. 70%), but there is also production occurring in Saskatchewan, British Columbia, the Northwest Territories, Manitoba, Nova Scotia and Ontario. Air pollutants from oil and gas production are released from a variety of sources: fugitive emissions from wells, processing facilities, storage facilities and pipelines; the combustion of fossil fuels to transmit and process crude oil and natural gas; as a waste by-product during processing.

The Regional Municipality of Wood Buffalo is an area of specific concern for pollutants from oil and gas production. This area encompasses Fort McMurray and the oilsands operations of northeastern Alberta, an area of intense oilsands bitumen extraction, upgrading and synthetic crude oil production. Acid deposition, ozone and particulate matter have all been identified as environmental concerns for the area. Ozone in particular has exceeded the 24-hour guideline an average of 135 days per year between 1990 and 1997, and since 1984 the annual average of 21 ppb exceeds the federal government's desirable level of 15 ppb. Owing to the high level of biogenic (natural) sources of VOCs in the area, the production of ozone follows the production of NO_X emissions from energy production for the oilsands operations.

5.2.9 Coal Mines for Ontario Power Plants

The source of coal for power plants in Ontario is approximately two-thirds from the eastern United States Appalachian area (West Virginia, Kentucky and Pennsylvania), where underground mining is used, and one-third from Saskatchewan and Wyoming, where open pit mining is used. Owing to the fact that coal mining is a relatively small part of the overall life-cycle emissions, with the exception of PM emissions for the Ontario scenarios, the emissions from coal mining were grouped into one "region." Given the breakdown of coal sources and their respective emission factors, approximately 98% of the PM emissions from coal mining for Ontario power plants can be allocated to the Appalachian area.

5.2.10 Northern Saskatchewan

The majority of uranium mining in Canada takes place in Northern Saskatchewan. This region will be allocated the emissions for uranium mining. However, since the relative life-cycle air emissions of a nuclear power–based transportation system are small compared with conventional transportation systems, the regional air quality impact of uranium mining will not be discussed in detail.

5.3 Data Sources

The vast majority of the data used in this LCVA are based on actual performance, either in testing environments or from actual field observations of commercial technologies, demonstration equipment, or working prototypes. In selecting technologies for this analysis, expert opinion has been used to select technologies considered most viable for the near (10-year) future. Sources of data include industry experts and technology developers for information on emerging technologies, and public resources and industry experts for conventional technologies.

By using data based on actual performance, this LCVA focuses on the performance of fuel systems today and avoids the uncertainty, complexity and bias of attempting to predict the future performance of every technology in the study. Undoubtedly, each technology will improve in the years to come, thus changing the value of the results. Even relatively certain changes in regulatory requirements, such as emission standards for vehicles, were not taken into account. However, it is of primary importance to attempt to determine the current status of society’s fuel supply alternatives if we are to better judge the best path to the future. Once an accurate “base case” is determined, a wide range of projections and future scenarios can be more quickly and easily evaluated and compared.

5.4 Description of the LCVA Model

Following the data collection process, the data were reviewed for accuracy and appropriateness by the technical steering committee before they were input into the Pembina Institute’s in-house LCVA software for aggregation of the system-wide results.

Comparison of the system results was done using several methods. Full system comparisons are based on the aggregated results of each of the aforementioned environmental stressor categories. Further detailed analyses were then performed by breaking down the systems by unit process and region to identify any “hot spots” – where there are significant releases of pollutants. Several system sensitivities were also investigated. These include on-board storage of liquid hydrogen instead of gaseous hydrogen for LDVs (centralized SMR system only), and gasoline production from oilsands as opposed to an aggregate of production sources in western Canada.

5.5 Environmental Inventory Analysis

The environmental inventory analysis was performed by first separating the scenarios into two classes: light-duty vehicles and buses. Each of these classes has a unique set of vehicles of interest to different audiences and, as will be demonstrated, has a unique set of results impacting the relative environmental performance of the scenarios studied. A sensitivity analysis and an assessment of resource consumption are also presented.

In general, the results for the three cities chosen are fairly consistent for comparable scenarios, with five notable exceptions:

1. transportation of hydrocarbons (crude oil, natural gas, methanol)
2. grid average electricity
3. Alberta coal production versus Ontario coal production
4. sulphur content in gasoline
5. greenhouse gas emissions from hydroelectricity

The most consistent difference occurring between regions is in the emissions from the transportation of crude oil, natural gas and methanol from Alberta to the respective cities. The transportation of these hydrocarbons constitutes at most approximately 22% of the life-cycle emissions in the Vancouver scenarios, up to approximately 7% in Calgary scenarios, and a maximum of approximately 34% of system emissions in one Toronto scenario.

A second major difference between the regional results occurs where the grid average electricity in each respective province is used for compression of gaseous fuels. This results in overall system emissions that are the highest in Calgary and the lowest in Vancouver due to the make-up of average grid power used for each province: British Columbia uses approximately 90% hydroelectricity and 10% natural gas; Ontario uses approximately 39% nuclear, 24% coal, 22% hydroelectricity, and 15% natural gas; and Alberta uses 86.6% coal, 9.7% natural gas, and 3.7% hydroelectricity and wind power.

A third major difference in the regional results is caused by the different emissions performance of the coal power plants and coal mining for Alberta and Ontario. By far the most obvious difference occurs in particulate matter emissions from coal mining. This is primarily due to the fact that two-thirds of the coal used in Ontario plants comes from the eastern United States Appalachian region, where underground mining was assumed to produce 1.4 kg of particulate matter per tonne of coal produced, as opposed to surface mining in Alberta, which produces 0.06 kg of particulate matter per tonne of coal.

The sulphur content of gasoline is another observable difference in life-cycle results between the cities studied. In Vancouver the sulphur content in gasoline is legislated to a maximum of 150 ppm, while the 1998 Ontario and Canadian averages were 530 ppm and 360 ppm respectively. The Canadian average was used as a default value for the Calgary scenario. Recent legislation will see the sulphur content in gasoline across Canada limited to 150 ppm between 2002 and 2004, and 30 ppm in 2005 (EC web site 2001).

The final notable difference in emission factors occurs between the hydroelectricity unit processes for British Columbia and Ontario. In British Columbia, BC Hydro has attempted to qualitatively compare the ability of its reservoirs to generate greenhouse gases with those in eastern Canada. This assessment was based on a number of key attributes, such as size, depth, amount of land flooded, and type of land flooded. It was concluded by BC Hydro that reservoirs in British Columbia are deeper, cover less land per unit of power generated, and have covered land with less vegetation than those in Quebec and Manitoba. Therefore, they are likely to emit fewer GHGs than those in Quebec. The LeGrande reservoir in Northern Quebec was estimated to emit 31 tonnes of CO_2 eq. / GWh of electricity generated (Gagnon 2000). For the purposes of this study, the assumption from BC Hydro's emission inventory that their reservoirs emit zero net greenhouse gases has been used, although it is noted that there is some scientific uncertainty in this area. In contrast, Ontario Power Generation, in its "Greenhouse Gas Action Plan – 2000," has attempted to quantify the GHG emissions from its hydroelectric operations. From this estimate, it was approximated that Ontario's hydroelectric reservoirs emit on average 6.8 tonnes of GHGs per GWh of electricity generated. It should be kept in mind that these assumptions may not be valid for a new hydroelectricity reservoir, given that the initial flooding of vegetated land results in generally higher GHG emissions through the first few years of impoundment (Gagnon 2000).

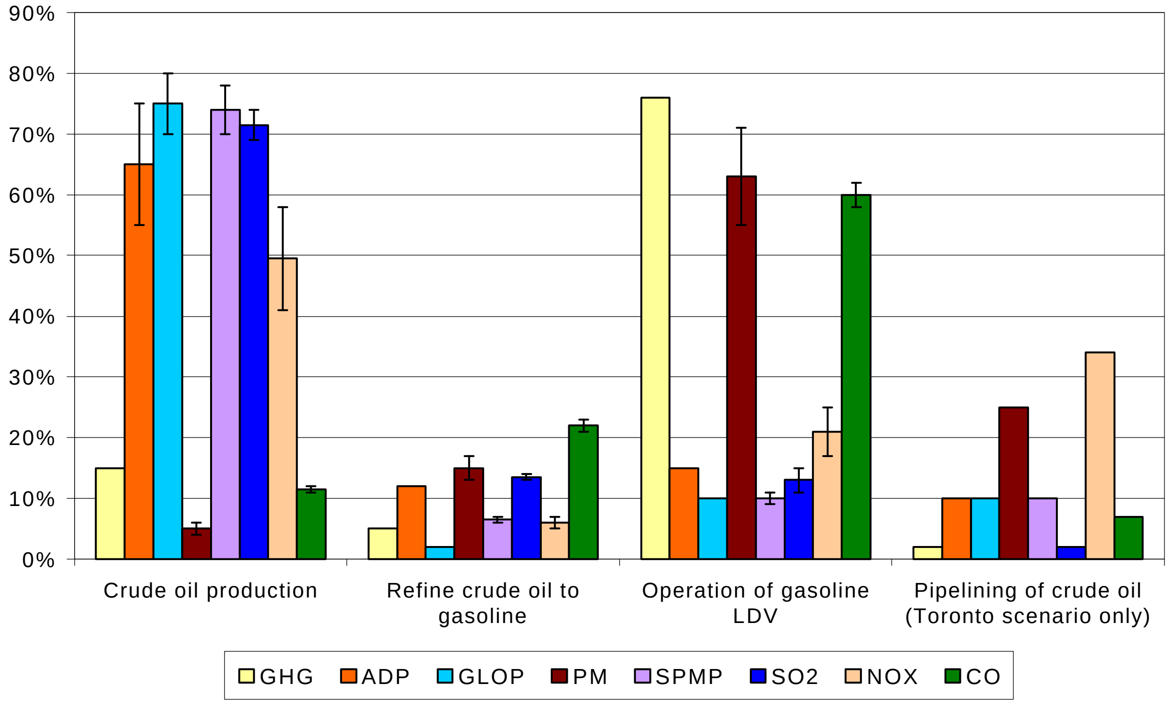
5.5.1 Light-Duty Vehicles

The overall results from system modelling of the light-duty vehicle scenarios are presented in Figures ES.2 to ES.4. These results have been normalized to reflect each scenario's relative performance to the base case (gasoline ICE light-duty vehicle), which was given a value of 1 for each stressor category.

Base Case – Gasoline ICE Light-Duty Vehicle

The gasoline ICE light-duty vehicle base case scenarios resulted in very similar breakdowns of emissions for the three cities studied. Figure 5.1 shows the breakdown of life-cycle emissions by the major emission source. The portion of the life-cycle emissions that remains undefined can be attributed to the unit processes not shown here and is typically less than 10% of the total. The fifth unit process on the chart indicates the emissions allocated to transportation of crude oil from Alberta to Southern Ontario for the Toronto scenario only. The corresponding emissions in the Calgary and Vancouver scenarios are not as large and therefore were not listed. This larger portion of the emissions allocated to crude oil pipelining in the Toronto scenario is also an indication that the life-cycle emissions are proportionately larger than the Calgary and Vancouver scenarios.

Figure 5.1 Major Emission Sources for the Gasoline ICE Light-Duty Vehicle Base Case Scenarios



*Percentage indicates the fraction of total life-cycle emissions allocated to each unit process. Average values for the three base case scenarios are presented. Error bars indicate the range of results for the three scenarios.

For GHG emissions, the majority (76%) are produced during vehicle operation. The remainder of emissions are a result of upstream fuel production.

In populated centres, where air quality is a significant concern, gasoline light-duty vehicles, along with gasoline production and distribution, have been identified as important sources of many of the criteria air pollutants. It is beyond the scope of this study to project the potential impact transportation will have on urban air quality in future years; however, a number of current trends provide some insight. For example, the number of vehicles on the road and the distances driven per vehicle are increasing while new vehicles are required to meet increasingly strict emission levels. Recently however, the average fuel consumption of new personal vehicles has increased to 1980 levels, due partly to increasing popularity of larger personal vehicles such as sport utility vehicles. As a result of these and other influences on air pollutant emissions, the concentration of air pollutants in Canadian cities is both increasing and decreasing, with the change depending on the pollutant and the region in question. Section 5.2, regarding Regional Context, describes some recent air quality measurements in the regions studied.

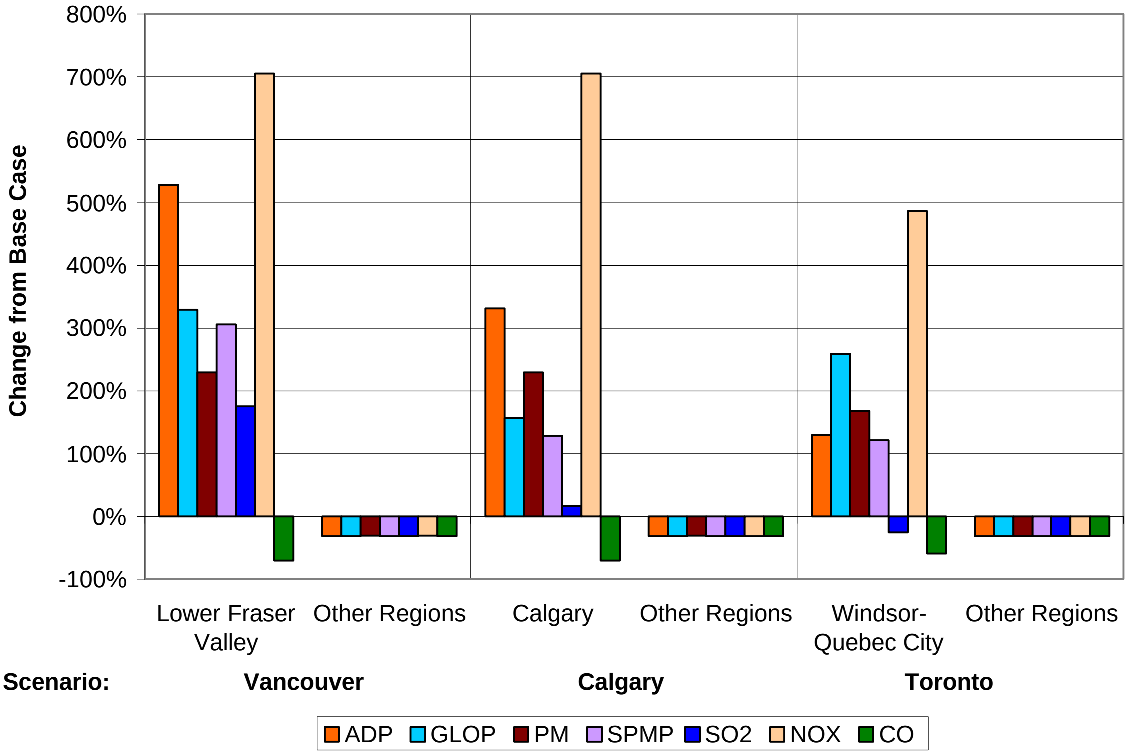
The significant emissions of certain air stressors at the source of crude oil production (ADP, GLOP, SPMP, SO_2 and NO_X) are also cause for concern. Air quality issues will worsen in these areas as oil production continues to expand.

Diesel ICE LDV

In the comparison of the diesel Volkswagen Jetta to the gasoline Ford Focus, the increased fuel efficiency of the compression ignition diesel engine is reflected in the 20% reduction in life-cycle greenhouse gases, as shown in Figures ES.2 to ES.4 (in the Executive Summary), but the potential impact on air quality is not as well defined. Figure 5.2 shows the increase in local air pollutant emissions by the diesel ICE system for each of the regions analyzed. ADP, GLOP and NOx emissions in Vancouver, Calgary and Toronto increase primarily because NO_X emissions are 8.5 times higher in the diesel Jetta than in the gasoline Focus. PM emissions in the cities are similarly affected because it is the nature of diesel combustion to produce particulates, unlike gasoline combustion. There are currently regulations in place in Canada to reduce diesel vehicle emissions to standards set for gasoline vehicles by 2008; however, gasoline vehicles are likely to maintain lower emissions owing to the head start in emission reductions they currently have. The comparative emission increase in the Windsor–Quebec City region is less than that in Calgary or the Lower Fraser Valley because there is a decrease in refinery emissions within the Southern Ontario region whereas, in the Calgary and Vancouver scenarios, the refinery emission reductions occur in the Edmonton region. The most noticeable improvement in criteria air pollutants is in carbon monoxide emissions, which are 78% less from the tailpipe for the diesel Jetta than for the gasoline Focus. Sulphur dioxide emission changes in the three cities vary significantly. This is due primarily to the variance in the sulphur content of gasoline, and the 31% reduction in refinery emissions in Southern Ontario. These differences in SO_2 emissions, however, are much smaller than the emissions reduction within the oil and gas field, which drive the life-cycle SO_2 emissions to an average of 26% less than the base case.

Overall, selection of a diesel ICE LDV in any of the cities is likely to significantly increase ADP, GLOP, PM, SPMP and NO_X emissions within the city. A doubling of air pollutants from light-duty vehicles would have a significant impact on air quality. At the same time, selection of a diesel ICE LDV instead of a gasoline ICE LDV will significantly benefit regions of upstream fuel production, through reduced crude oil demand, and the global environment, through the reduction of life-cycle GHG emissions.

Figure 5.2 Change in Regional Emissions for the Diesel Jetta Compared with the Gasoline Focus

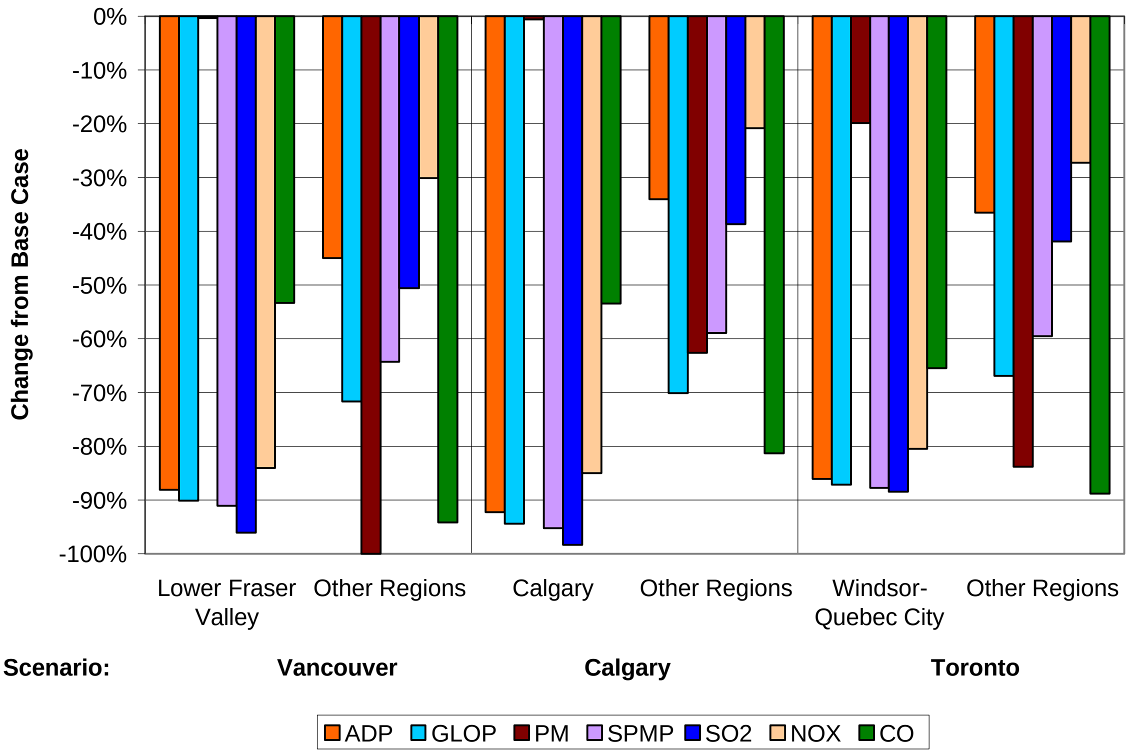


*The majority of emissions in “Other Regions” occur in Alberta for all scenarios.

Natural Gas ICE Light-Duty Vehicle

The natural gas–powered Honda Civic GX offers significant life-cycle emissions reduction in all of the stressor categories evaluated compared with the gasoline-powered Ford Focus. The greenhouse gas emission reductions amounted to 39% in Vancouver, 35% in Calgary, and 34% in Toronto. The two primary reasons for the difference in emission reductions for the three cities are the unique electricity sources used to meet the compression requirements of NGVs, and the varying distances of natural gas transport. In general, emissions are reduced in every region except where electricity generation takes place in Alberta and where natural gas is pipelined instead of gasoline (through B.C. and Alberta). Figure 5.3 shows the change in regional emissions when compared with the base case. In the major urban regions a greater than 80% decrease in emissions occurs in almost every stressor category with the exception of CO (greater than 50% reduction) and PM (brake and tire wear is assumed to be identical for the two vehicles). In the Edmonton region, a complete elimination of refinery emissions takes place. Figures ES.2 to ES.4 (executive summary) show the reductions in life-cycle emissions for the natural gas LDV scenarios, with the largest decreases (greater than 60%) occurring in GLOP, SPMP and CO.

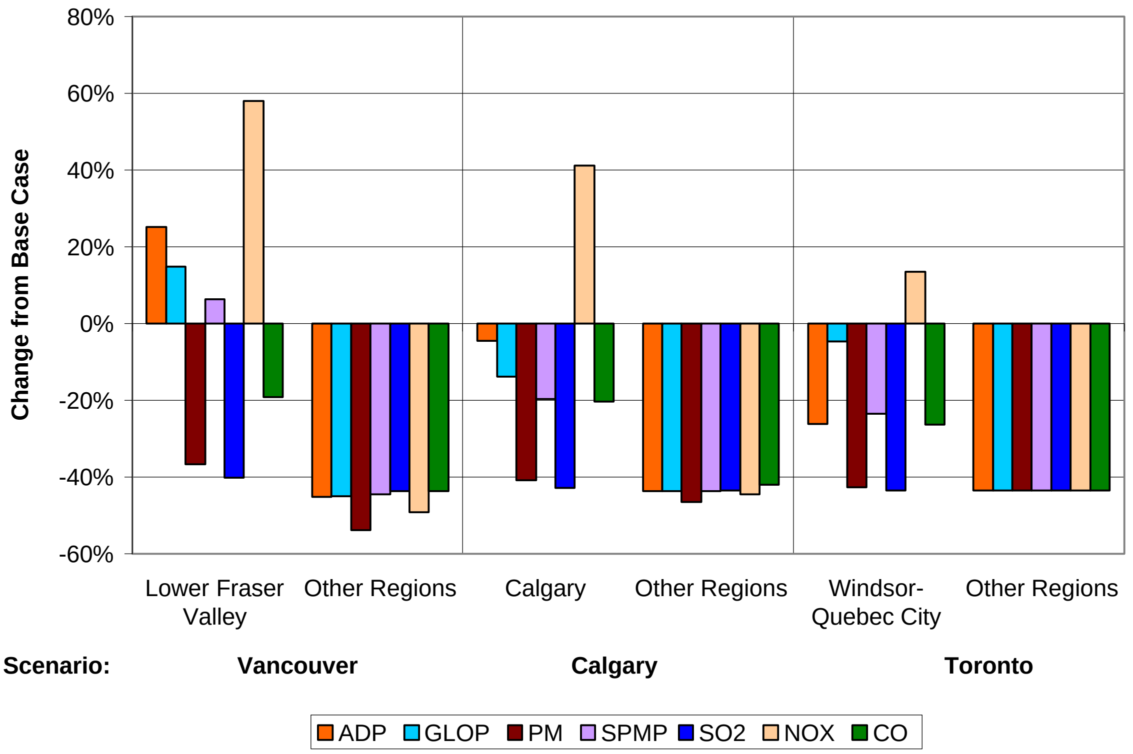
Figure 5.3 Change in Regional Emissions for the Natural Gas Civic Compared with the Gasoline Focus



Gasoline Hybrid Electric Vehicle (HEV)

The Toyota Prius HEV consumes 43% less gasoline than the Ford Focus, allowing it to correspondingly reduce its life-cycle greenhouse gas emissions and its upstream non-greenhouse gas emissions. However, the non-greenhouse gas emissions from the Prius itself are, in some cases, higher than those of the Focus. The result is an increase in tailpipe emissions within the regions of vehicle operation, most notably NO_X, as shown in Figure 5.4, while others decrease substantially; CO, PM, SO_2 have the largest decrease. Overall, this drives the life-cycle air emission reductions to a minimum of 24% for NO_X and greater than 37% for GHG, ADP, PM, SPMP and SO_2 emissions.

Figure 5.4 Change in Regional Emissions for the Prius HEV Compared with the Gasoline Focus



Methanol FCV

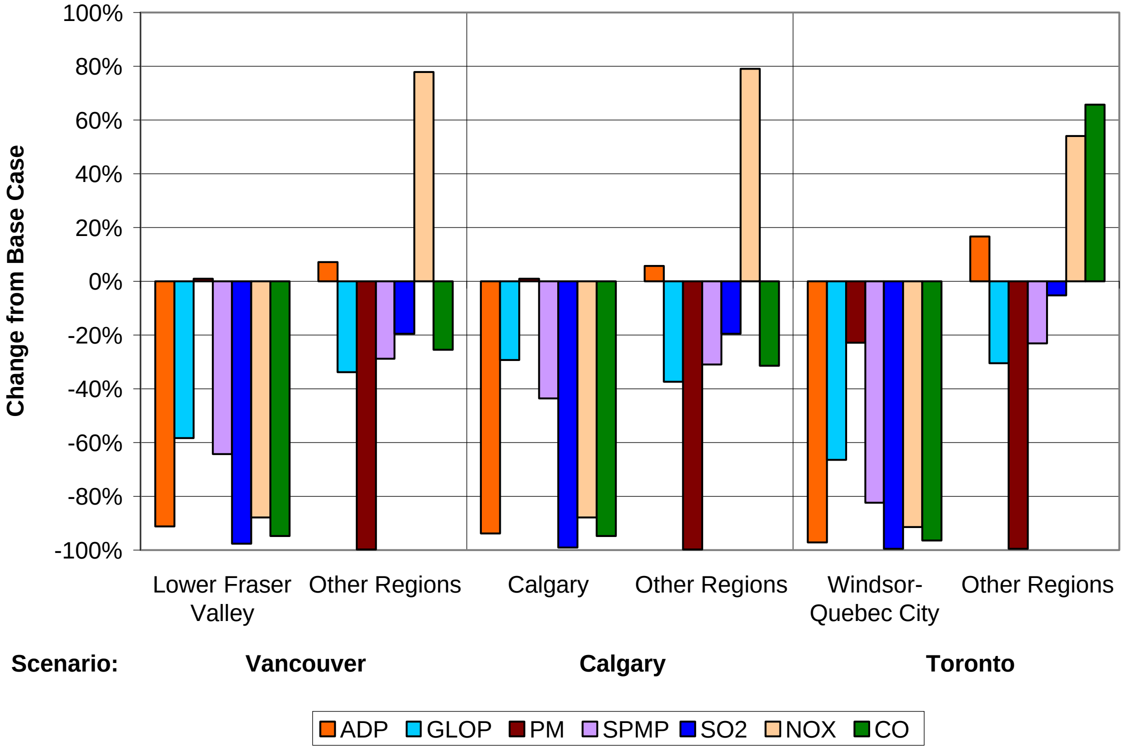
Fuel cell vehicles with on-board methanol processing (MFCVs), also known as Indirect Methanol FCVs, have nearly zero tailpipe emission of criteria air contaminants, but on a life-cycle basis, current technologies result in an increase or little change in some stressor categories, while the majority decrease significantly when compared with the gasoline Focus base case. Because the NECAR 5 MFCV is currently in the testing and development stage, the methanol fuel consumption has not yet been fully optimized. The authors roughly estimate a potential reduction of 17% from the results presented through a vehicle weight reduction program for the NECAR 5. Future technology advances may reduce the fuel consumption of MFCVs even further.

Nonetheless, the NECAR 5 does have the potential to significantly reduce vehicle emissions in each of the three cities, as shown in Figure 5.5. Exceptions are in PM emissions, where brake and tire wear are equal for both vehicles, and VOC emissions, which contribute to ozone and secondary PM production. VOC emissions from the evaporation of methanol were assumed to be 60% of gasoline on a volume basis, but, since the energy density of gasoline is higher than methanol, a larger volume of methanol is required per kilometre travelled, thereby producing more VOC emissions during fuel storage and transmission. A more varied change in air emissions occurs in the fuel production and distribution unit processes. The majority of these emissions occur in the categories marked “Other Regions,” as shown in Figure 5.5. The largest spatial change in emissions will undoubtedly occur from the regions of oil refining to the regions of methanol production. The 66% increase in CO emissions in the upstream regions of the Toronto scenario are due to the fact that gasoline system’s refinery emissions are included within the city region for this scenario while the methanol plant emissions does not. There are also noticeable changes in both the oil- and gas-producing regions, due to the change in production from crude oil to natural gas, and along transportation routes where rail is used instead of pipelines to transport methanol long distances.

On a life-cycle basis, as shown in Figure ES.2 to ES.4, GHG emissions decrease approximately 8%, while ADP decreases only 9% on average. NO_X emissions are of particular concern since they increase between 20% and 41%, mostly due to methanol and natural gas production. The remainder of the stressor categories present noticeable decreases, with CO seeing by far the largest drop (63% to 70%), due primarily to the high CO emissions from gasoline vehicles.

In short, there are significant reductions in both vehicle emissions and some life-cycle emissions resulting from the operation of the NECAR 5, however, there is also little change in life-cycle GHG and ADP emissions and a significant increase in upstream NO_X emissions.

Figure 5.5 Change in Regional Emissions for the NECAR 5 MFCVs Compared with the Gasoline Focus



Decentralized SMR-Based FCV

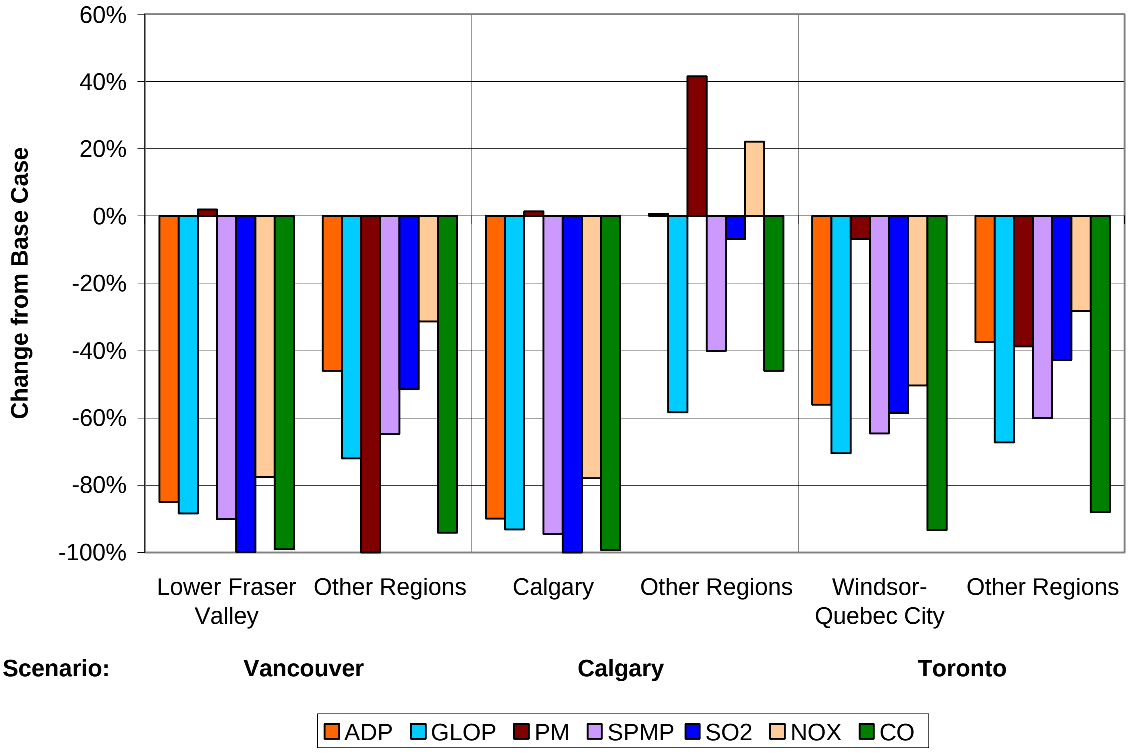
The life-cycle emissions of the decentralized steam methane reformer (SMR)–based NECAR 4a scenarios are dependent on the electricity source used to power both the reformer and the hydrogen compressor (approximately 4.4 kWh per kg hydrogen). The Vancouver scenario demonstrates a system that uses zero-emission electricity production to supply 90% of the electricity requirements. As shown in Figure ES.2, this results in substantial decreases in emissions in all stressor categories ranging from 34% to 97% when compared with the gasoline Focus base case. Alternatively, the Calgary scenario demonstrates the effect that electricity generation from almost solely fossil fuels has on the decentralized SMR system. The life-cycle performance of the Calgary scenario results in a range of emission levels when compared with the gasoline Focus base case, from a 14% increase in PM to a 78% decrease in CO, as shown in Figure ES.3.

As seen in Figure 5.6, some of the air emission reductions in the Calgary region result in increases of air emissions in other regions, mostly those of electricity generation and resource extraction within Alberta. In the Toronto scenario, the combination of low emission sources of electricity and fossil fuel–based electricity results in life-cycle emissions between the Vancouver and Calgary results. However, the emission reduction in the Windsor-Quebec region is not nearly as substantial as those in the Lower Fraser Valley and in Calgary. This is due to the fact that a significant amount of electricity comes from fossil fuel power plants within the region of vehicle operation.

In comparison with other vehicle and fuel supply systems, the decentralized SMR-based system using the NECAR 4a has life-cycle emissions ranging from slightly lower than the natural gas Civic system in the Vancouver scenario to noticeably higher in the Calgary scenario. Given their position on the technology maturity curve described in Section 3.2, fuel cell vehicles and small-scale steam methane reformers are expected to have efficiency improvements that will decrease the life-cycle emissions of this system. It should be kept in mind; however, that the small-scale SMR technology used for this system is still a prototype unit and is claimed to have lower natural gas consumption than many commercial large-scale SMR units, although it also has higher electricity consumption.

Ultimately, the environmental performance of the decentralized SMR FCV system will depend on the overall system design. If low-impact, renewable electricity sources are used to power the reformer and compressor, the system provides major emission reductions in all stressor categories. If a mix of low emission and fossil fuel–based electricity sources are used, then the environmental burden can either be decreased or increased and, depending on where the electricity generation takes place, a large portion of the emissions can be shifted into other regions.

Figure 5.6 Change in Regional Emissions for the NECAR 4a FCV Using Decentralized SMR Compared with the Gasoline Focus

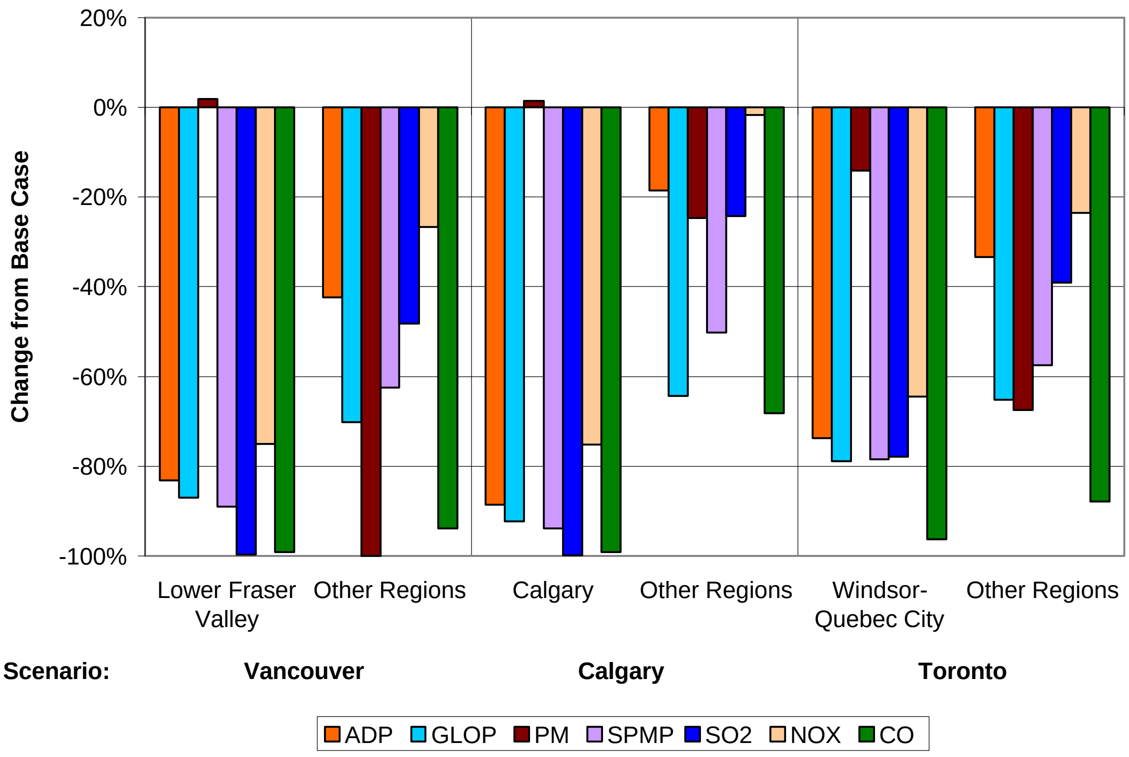


Centralized SMR-Based FCV

The centralized production of hydrogen using steam methane reformers presents life-cycle results that are very similar to the decentralized system, except that there is approximately 47% less electricity required for the reformer and the hydrogen compressors, and 8% more natural gas required due to the SMR fuel conversion efficiencies. Once again, the Vancouver and Toronto scenarios show lower life-cycle emissions than the Calgary scenario due to the source of electricity used in each province, as shown in Figures ES.2 to ES.4. Also similar to the decentralized SMR system is the fact that the centralized SMR system with the NECAR 4a compares closely with the natural gas Civic system. Accordingly, fuel cell vehicles are expected to have efficiency improvements as the technology matures, thus decreasing the life-cycle emissions of this system.

Currently, the regional breakdown of results, as shown in Figure 5.7, shows a reduction in emissions for every stressor category in all regions with a few exceptions: PM emissions in Vancouver and Calgary and NO_X emissions in Calgary's upstream regions show little change owing to the vehicle brake and tire wear, and the coal power plant emissions, respectively.

Figure 5.7 Change in Regional Emissions for the NECAR 4a Using Centralized SMR Compared with the Gasoline Focus



Electricity-Based Vehicle Operation (FCV & EV)

The main advantage of using electrolysis to produce hydrogen for fuel cell cars or using battery electric cars is that they produce no local air pollution, with the exception of particulate matter from brake and tire wear. These systems shift most of the environmental air emissions of vehicle operation away from the vehicle and to the production of electricity. It should be kept in mind that the following discussion is limited to the specific stressor categories chosen for quantification in this study and will not reflect their entire life-cycle environmental, social and economic impacts. For example, wind-powered vehicle systems for FCVs and EVs will have nearly identical air emissions, but the issues surrounding resource consumption, vehicle range and cost will be very different. A qualitative discussion of further issues can be found in later sections of this report.

The life-cycle air pollutant emissions of the EV1 compared with the NECAR 4a FCV rely, for the most part, on the relative electricity requirements for each system. Overall, the NECAR 4a requires 2.9 times more electricity for hydrogen produced through electrolysis than the EV1 needs to travel an equivalent distance. Since all of the air emissions for these two systems, except PM from brake and tire wear, are produced through electricity generation and its upstream activities, there is a direct correlation between the systems' life-cycle emissions and electricity generation requirements. This relationship applies to all of the electrolysis and electric vehicle systems, but is most evident in the natural gas and coal–based systems, as opposed to the systems with almost no life-cycle air pollutant emissions.

Wind-Based Electricity (FCV & EV)

Wind power generation is a zero-emission electricity generation technology. The only emission quantified from the operation of the entire system was the generation of particulate matter from brake and tire wear. This value is lower for the EV1 than the NECAR 4a FCV because it was assumed that the EV1 would use 30% regenerative braking on average to recover and store energy from the wheels, and thus reduce the particulate matter generated from mechanical braking. Other zero-emission electricity generation technologies likely to have similar life-cycle results are photovoltaics, solar thermal power, low-impact hydroelectricity, geothermal power, tidal power and wave power (all of these technologies will have different life-cycle emissions from their raw material extraction, manufacturing and maintenance, which are outside the system boundary in this LCVA).

Hydroelectricity-Based Electricity (FCV & EV)

Conventional hydroelectricity power generation with the use of large human-made reservoirs also resulted in extremely low life-cycle emissions. Emission of greenhouse gases, however, does occur from most natural water bodies and an effort was made to quantify these amounts. The resulting life-cycle GHG emissions from a hydroelectricity-based FCV or EV system are approximately 2% of the base case in Ontario and effectively zero in British Columbia.

Nuclear Power-Based Electricity (FCV & EV)

Nuclear power generation is another technology with very low life-cycle emissions. Even though uranium needs to be mined, transported and processed, the emissions per unit of electricity generated are extremely small because the amount of uranium required is small. In comparison with the base case, emissions from a nuclear power–based vehicle system in Toronto are nearly zero, with the exception of PM emissions from vehicle brake and tire wear. The stressor category with the next largest relative emission was sulphur dioxide, with less than 2% of the base case emissions.

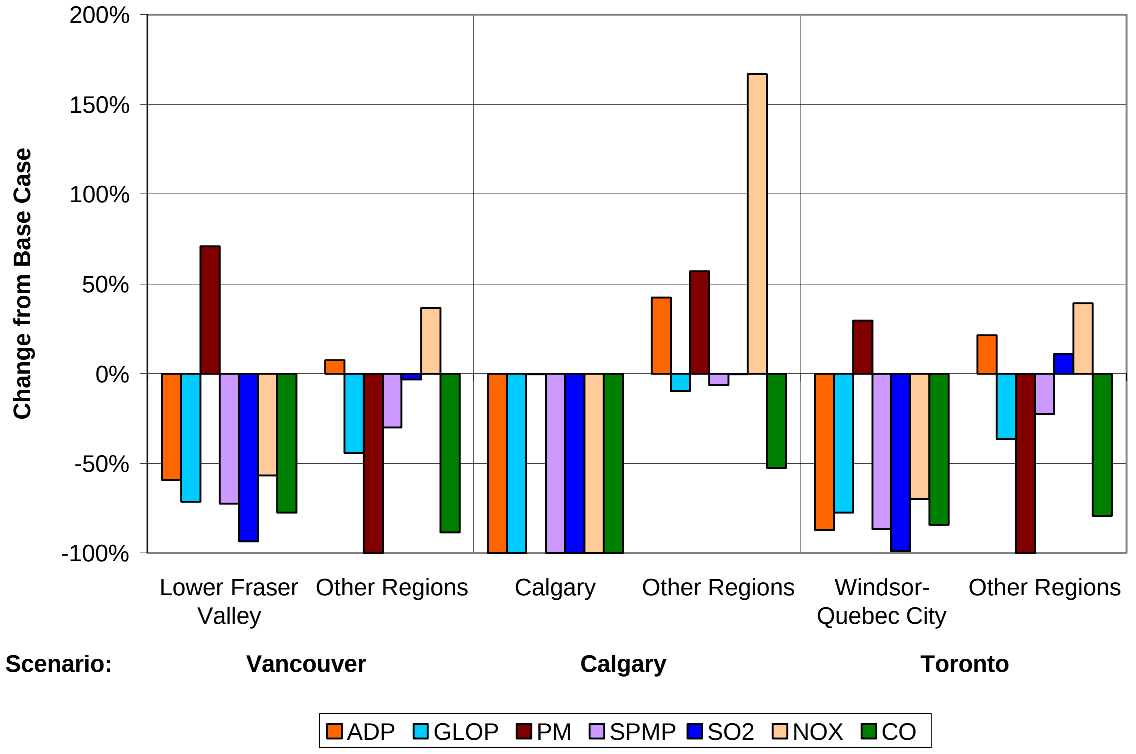
Natural Gas-Based Electricity

Natural gas power can be used in all three provinces for incremental power generation. This means if additional electricity demand were to be placed on the grid, it may result in the increased output of natural gas power plants. In both British Columbia and Ontario, it was assumed that selective catalytic reduction (SCR) would be used in conjunction with low NO_X burners to reduce the plant's NO_X emissions. This is a result of recent trends in both provinces to reduce the emission of criteria air contaminants in densely populated areas. In Alberta, it is assumed only low NO_X burners will be used, as this is the easiest method of achieving the legislated requirements.

Natural Gas-Based Electrolysis (FCV)

Using natural gas power plants for hydrogen generation through electrolysis shifts nearly all air emissions away from the vehicle tailpipe to the natural gas power plants and upstream natural gas supply system. In the Lower Fraser Valley, Calgary, Windsor-Quebec City regions there is a decrease in all stressor categories, as shown in Figure 5.8, except PM, which increases in two of the regions due to power plant emissions. The remaining regions all demonstrate either an increase or little change in ADP, SO_2 and NO_X emissions. For the Calgary scenario, NO_X emissions in Alberta are twice as large as the base case emissions due to the lack of selective catalytic reduction of NO_X at the power plants. The other stressor categories, GLOP, SPMP and CO, either decrease or have little change in most regions, and on a life-cycle basis, all decrease between 24% and 83%. Conversely, the life-cycle emissions of GHG, ADP, PM and NO_X generally increase with some small exceptions (ADP and PM emissions in the Toronto scenario decrease slightly due to fewer emissions for natural gas pipelining compared with crude oil pipelining). Overall, fuel cell vehicles powered with natural gas–based electrolysis show considerable benefit to the cities where vehicle operation takes place, but on a life-cycle basis, the results show both benefits and disadvantages to choosing such a system.

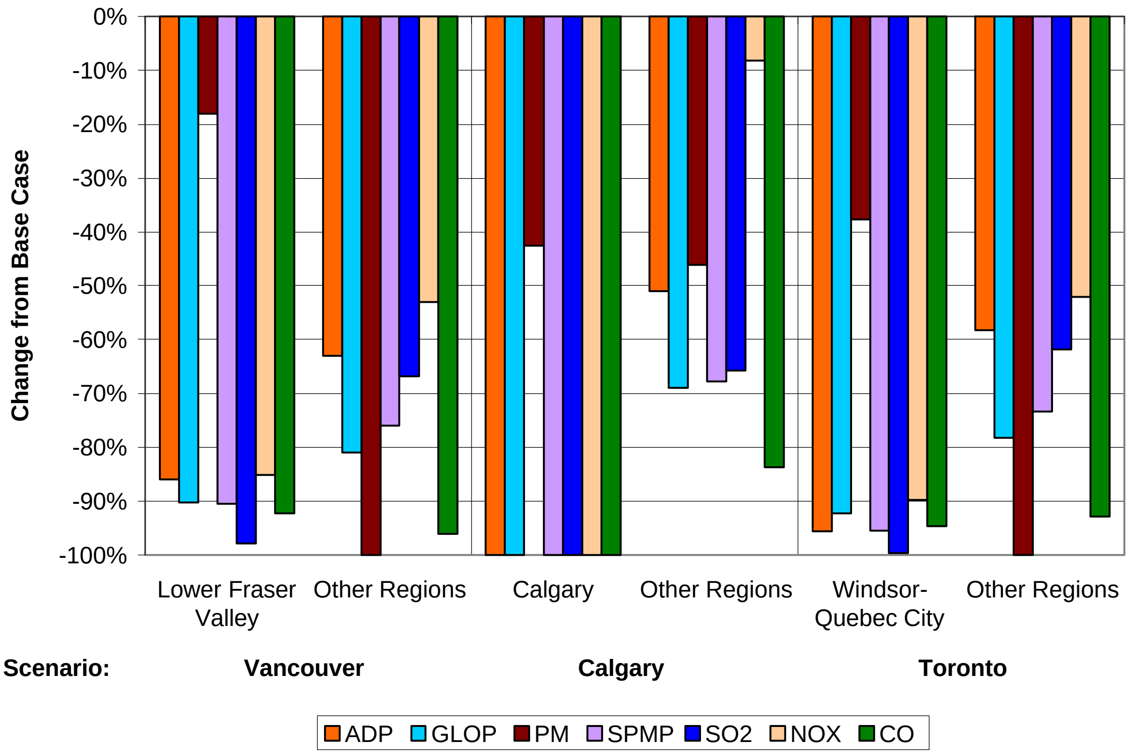
Figure 5.8 Change in Regional Emissions for the NECAR 4a FCV Using Natural Gas–Based Electrolysis Compared with the Gasoline Focus



Natural Gas-Based EV

Operation of a GM EV1 that is recharged from a natural gas power plant results in a significant improvement in air pollutant emissions over the base case in nearly all stressor categories in the various regions evaluated. There is an obvious shift in pollutant sources from the areas of vehicle operation and gasoline production to the power plant locations. However, both the life-cycle and regional emissions shown in Figure 5.9 demonstrate an overall benefit for the electric vehicle, due primarily to the increased fuel efficiency of the EV1 over the Focus and the superior emissions control capabilities of a large power plant compared with a vehicle.

Figure 5.9 Change in Regional Emissions for the EV1 Using Natural Gas–Based Electricity Compared with the Gasoline Focus



One area of potential concern given the results is the location of natural gas electricity generation in Alberta. Many of the emissions from Calgary, Edmonton, and the oil and gas field are shifted, in part, to the power plants. This may result in a concentration of emissions in areas of large power plants or several smaller ones, thus having a more intense environmental influence in those areas.

Overall, however, the results show that the selection of an EV recharged from a natural gas power plant will have a large net benefit to the environment in all three of the scenarios. With the exception of NO_X emissions in the Calgary scenario, every stressor category demonstrates a reduction of life-cycle emissions of between 44% and 94%, as shown in Figure ES.2 to ES.4.

Coal-Based Electricity (FCV & EV)

The life-cycle results show that a transportation system powered by coal emits a very large amount of air pollutants when compared with the base case. On a life-cycle basis, stressor category emissions increase between 54% and 1400% for the FCV scenarios, and up to 440% in the EV scenarios. The EV scenarios do show some decrease in life-cycle emissions for GLOP, CO and GHG (Toronto scenario only) emissions, but the remainder of the stressor categories all increase. As shown in Figures 5.10 and 5.11, these systems do shift many of the air pollutants almost entirely away from particular regions (the Calgary region, and the resource production regions for the Toronto scenario). However, these emissions are generally many times more intense at the coal power plants. Since there are only a handful of large coal power plants in Alberta and Ontario, the total life-cycle emissions will be concentrated in the areas surrounding the plants. Particulate matter is emitted at high levels within areas of both coal mining (particularly the northeastern U.S. Appalachian region) and electricity production.

Figure 5.10 Change in Regional Emissions for the NECAR 4a FCV Using Coal-Based Electrolysis Compared with the Gasoline Focus

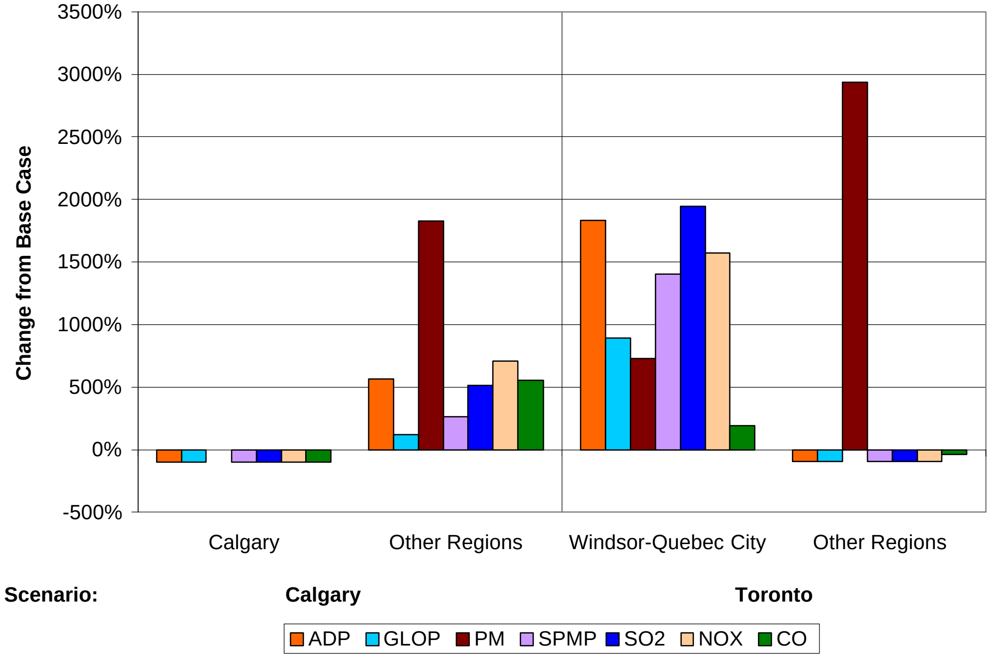
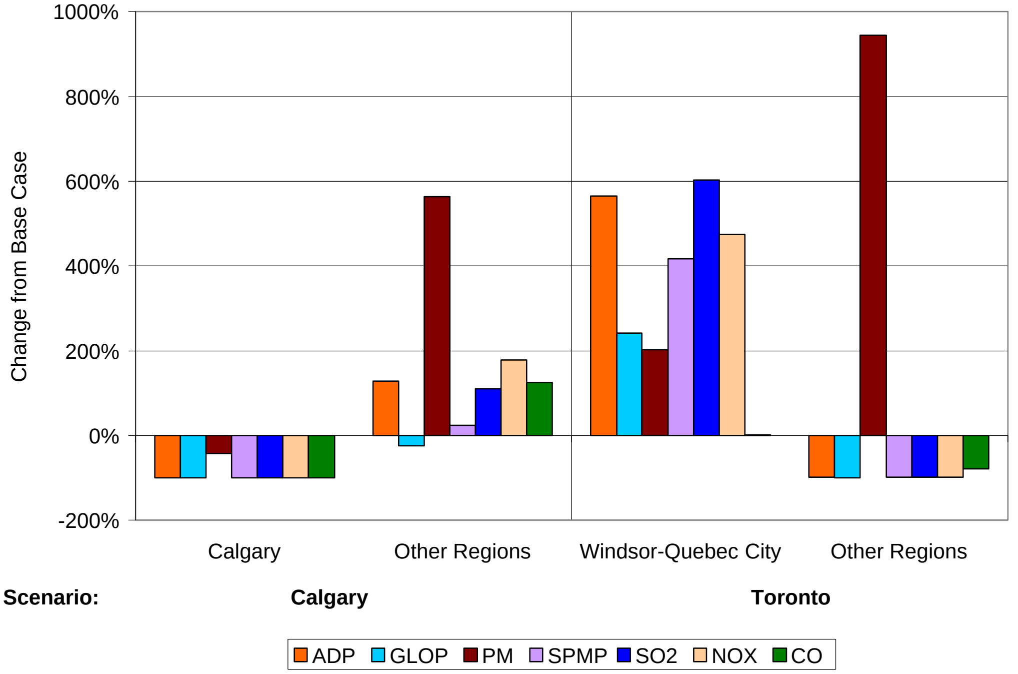


Figure 5.11 Change in Regional Emissions for the EV1 Using Coal-Based Electricity Compared with the Gasoline Focus



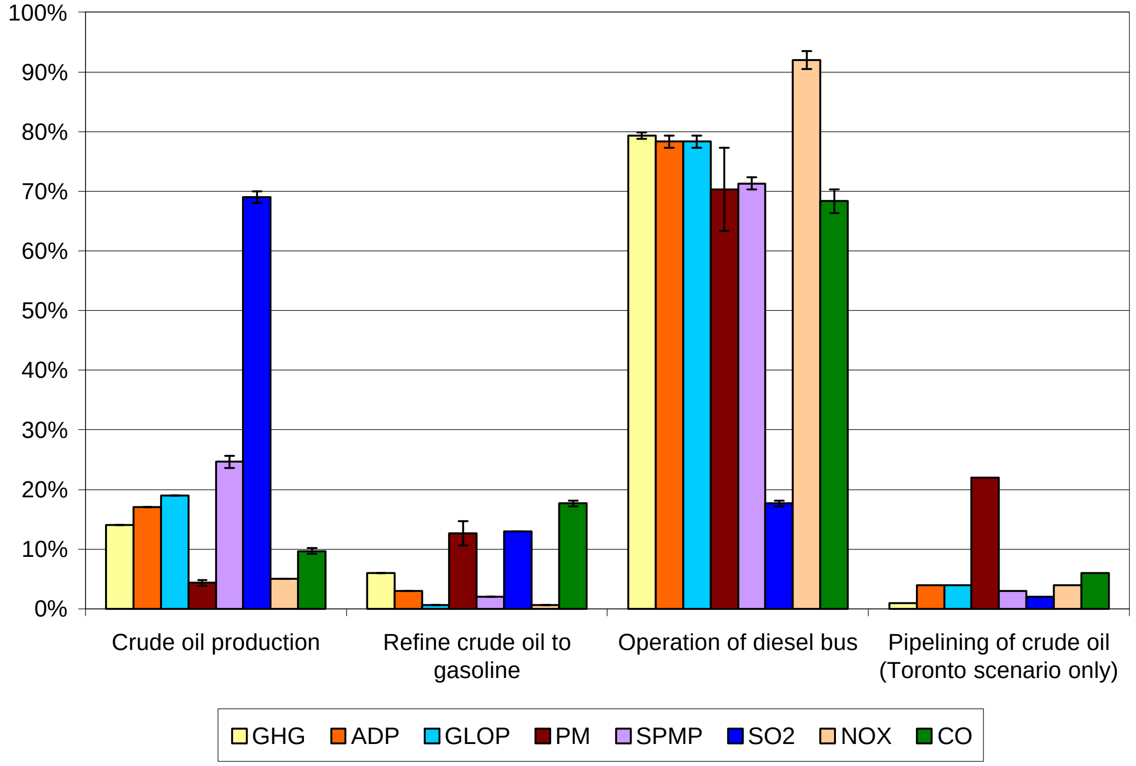
5.5.2 Buses

The overall results from the system modelling in the bus scenarios are presented in Figures ES.5 to ES.7. The results presented in these figures have been normalized to reflect each scenario's relative performance to the base case (Diesel ICE Bus), which was given a value of 1 for each stressor category.

Base Case – Diesel ICE Bus

The diesel ICE bus base case scenarios resulted in very similar breakdowns of emissions for the three cities studied. Figure 5.12 shows the breakdown of life-cycle emissions by major emission source. The portion of the life-cycle emissions that remains undefined can be attributed to the unit processes not shown here and is typically less than 10% of the total. The fifth unit process on the chart indicates the emissions allocated to transportation of crude oil from Alberta to Southern Ontario for the Toronto scenario only. As shown, PM emissions are the only stressor category that is significantly affected by crude oil pipelining in the Toronto diesel bus scenario. The corresponding emissions in the Calgary and Vancouver scenarios are not as large and therefore were not listed.

Figure 5.12 Major Emission Sources for the Diesel ICE Bus Base Case Scenarios

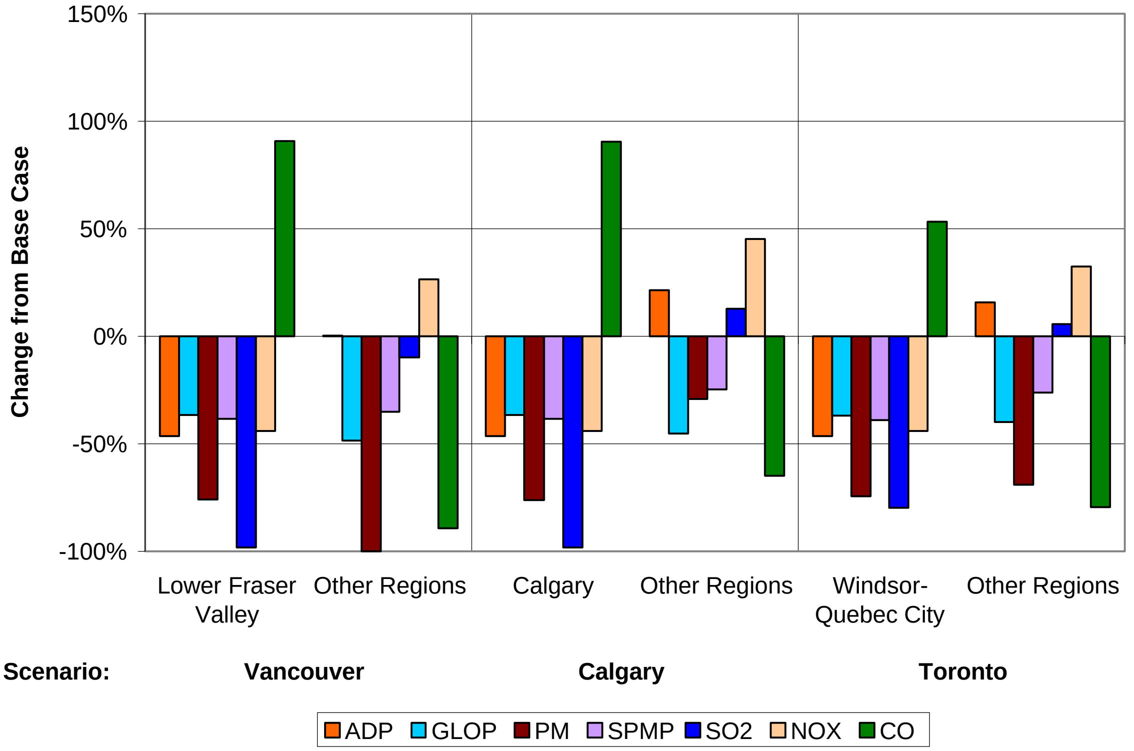


*Percentage indicates the fraction of total life-cycle emissions allocated to each unit process. Average values for the three base case scenarios are presented. Error bars indicate the range of results for the three scenarios.

Natural Gas ICE Bus

The natural gas–powered transit bus offers significant life-cycle emissions reduction in most of the stressor categories evaluated, with the exception of GHG and CO, compared with the diesel-powered bus. Greenhouse gas emissions ranged from 5% to 13% greater than the diesel bus base case. Once again, the difference in emission reductions between the three scenarios results from the mixture of electricity sources within each province (used primarily for compression of natural gas) and the varying natural gas transmission distances. Figures ES.5 to ES.7 shows reductions (greater than 30%) in life-cycle emissions for the natural gas bus scenarios occurring in ADP, GLOP, PM, SPMP and NO_X , with the largest decrease occurring in PM (82% decrease from the base case). As shown in Figure 5.13, the major urban regions demonstrate a greater than 37% decrease in criteria air contaminant emissions in almost every stressor category with the exception of CO, which increases in all three cities owing to the tailpipe emissions of the natural gas bus itself. Within the upstream regions, there is also a general decrease in most emission categories, with the exception of NO_X, which is more than 26% higher in the regions of resource production and transmission, while ADP and SO_2 emissions are within 21% of the base case.

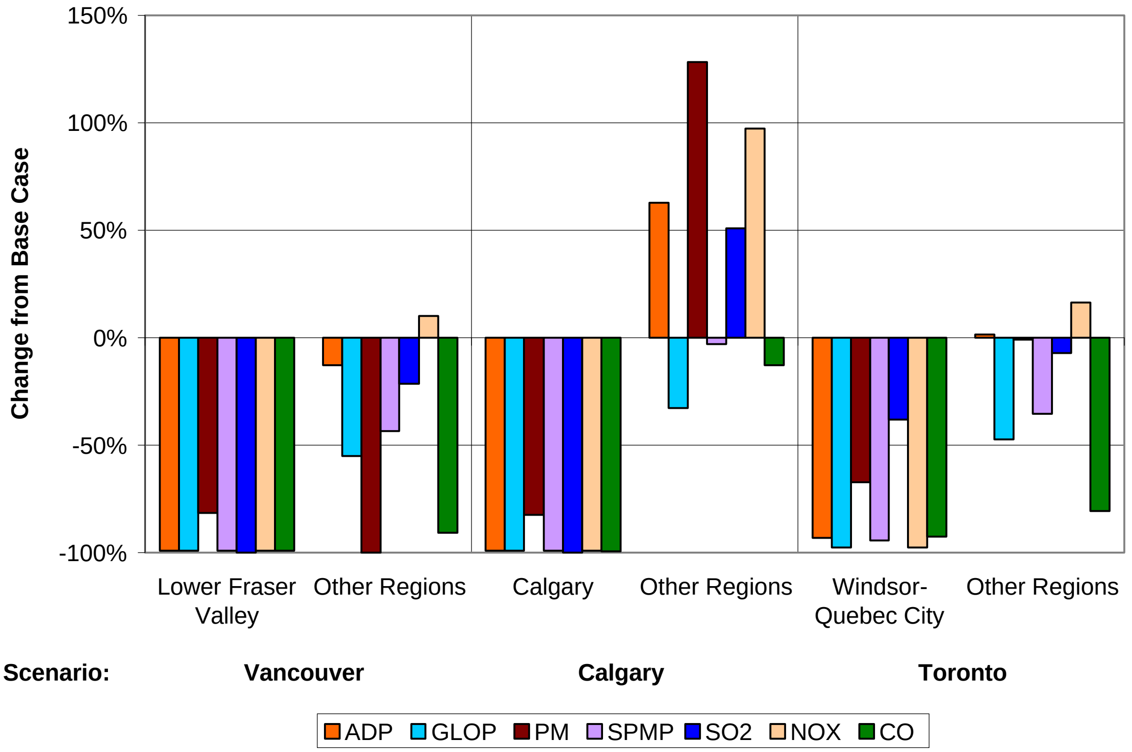
Figure 5.13 Change in Regional Emissions for the Natural Gas Bus Compared with the Diesel Bus Base Case



Decentralized SMR-Based Fuel Cell Bus

The air emissions of the decentralized SMR NEBUS scenarios vary from city to city due to differences in regional electricity sources. For the most part, all three scenarios show significant decreases in life-cycle air emissions when compared with the diesel bus base case, as shown in Figures ES.5 to ES.7. The only exception is GHG and SO_2 emissions in the Calgary scenario, where coal power plants are a large supplier of electricity, and they were consequently assumed to supply a large portion of the electricity required for production and compression of hydrogen. The source of electricity was also influential in the amount of emissions decrease occurring in GHG emissions. In the Calgary scenario, GHG emissions increased only 3%, while they decreased approximately 25% in the Vancouver scenario, where less carbon-intensive electricity is typically used. In the Calgary and Toronto scenarios, life-cycle PM emissions decrease less than many of the other stressor categories, primarily because of the electricity production by coal power plants. As shown in Figure 5.14, there are substantial decreases in emissions in all stressor categories of criteria air contaminants within each of the three cities of operation, owing to the zero tailpipe emissions of a fuel cell bus and relatively low air pollutant emissions from steam methane reforming. Emission increases in the upstream regions of the Calgary scenario are again the result of coal-fired power plant emissions. The life-cycle performance of the fuel cell bus is expected to improve even further as the technology matures. It should be kept in mind that the small-scale SMR technology used for this system is still a prototype unit and is claimed to have lower natural gas consumption than many commercial large-scale SMR units, although it also has higher electricity consumption.

Figure 5.14 Change in Regional Emissions for Decentralized SMR Hydrogen FC Bus Compared with the Diesel Bus Base Case

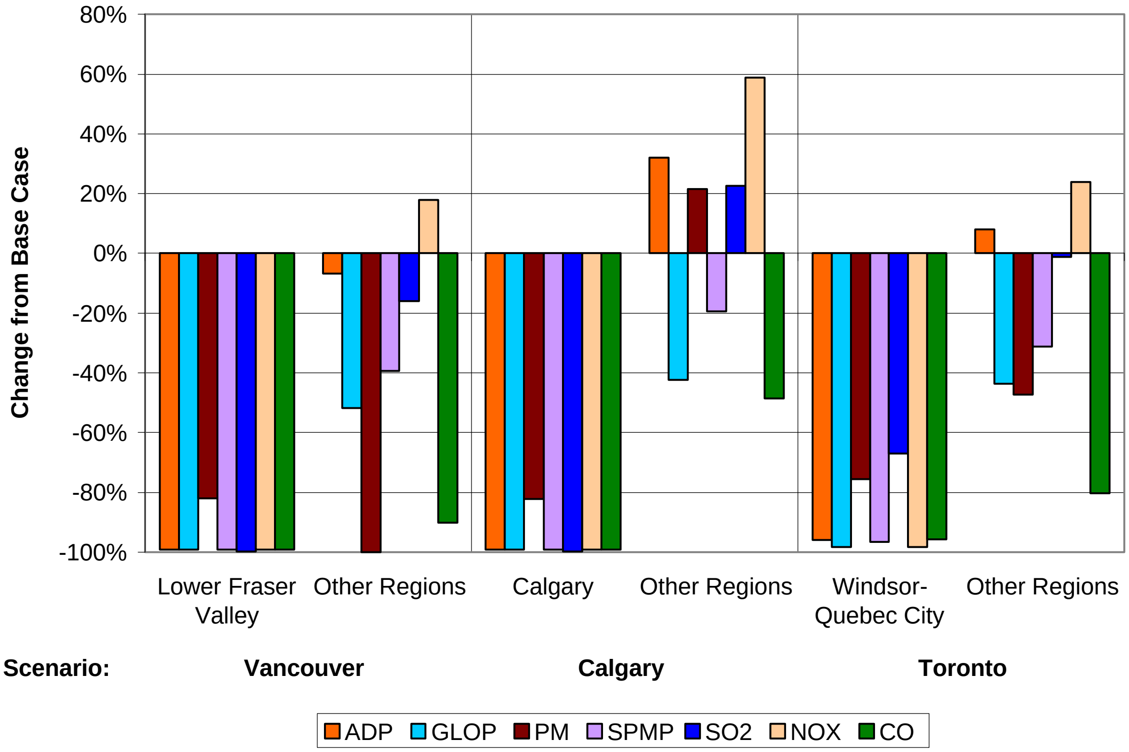


Ultimately, the environmental performance of the decentralized SMR fuel cell bus system will depend on the overall system design and fuel efficiency of the bus. If low-impact, renewable electricity sources are used for the reformer and compressor, the system provides major emission reductions in all criteria air contaminants. If highly carbon-intensive electricity sources are used, there may still be life-cycle emission reductions, but a large environmental burden may be shifted to regions of electricity generation.

Centralized SMR-Based Fuel Cell Bus

The centralized production of hydrogen using steam methane reformers presents life-cycle results that are very similar to the decentralized system, except that there is approximately 47% less electricity required for the reformer and the hydrogen compressors, and 8% more NG required due to the efficiencies of the specific SMR units used in the analysis. Therefore, the results are less sensitive to the source of electricity than the decentralized SMR scenarios, but high-emission electricity sources remain as noticeable contributors to all stressor categories, particularly in the regions of electricity generation. The life-cycle results show greater than 58% reductions in every stressor category except GHG and SO_2 when compared with the diesel bus base case. GHG emissions decrease between 6% and 20% while SO_2 emissions decrease between 0% and 31%. The regional breakdown of results, as shown in Figure 5.15, shows major reductions in emissions for nearly every stressor category in most regions. Exceptions occur where coal-fired power plants exist, and where natural gas transmission takes place, due to higher NO_X emissions from natural gas than from crude oil transmission. Once again, the life-cycle performance of the fuel cell bus is expected to improve even further as the technology matures.

Figure 5.15 Change in Regional Emissions for Centralized SMR Compared with the Diesel ICE Base Case



Electricity-Based Vehicle Operation (Fuel Cell Bus & Electric Trolley Bus)

The electrolysis-based fuel cell buses and the electric trolley buses have very similar attributes. All of the life-cycle emissions for these two system types, with the exception of particulate from brake and tire wear, occur upstream from the point of electricity consumption. Therefore, the emissions for each of these systems are directly dependent on its electricity requirements. Based on presently available data, 2.9 times more electricity is required for the NEBUS to produce hydrogen through electrolysis than the electric trolley bus needs to travel an equivalent distance; therefore, the life-cycle emissions will be similarly proportioned. There is a general expectation that this difference will decrease as fuel cell buses near commercialization.

The following discussion deals only with the emission of the air pollutants selected for analysis and does not contain a complete comparison of their life-cycle performance. A qualitative discussion of further issues regarding the vehicle types can be found in later sections of this report.

Wind-Based Electricity (Fuel Cell Bus & Electric Trolley Bus)

Wind power generation is a zero-emission electricity generation technology. The only emissions quantified from the operation of the entire system consisted of the generation of particulate matter from brake and tire wear. This value is 12% of the PM emissions in the diesel bus scenario. Other zero-emission electricity generation technologies likely to have similar life-cycle results are photovoltaic, solar thermal power, low-impact hydroelectricity, geothermal power, tidal power and wave power (these technologies have different life-cycle emissions from their raw material extraction, manufacturing and maintenance, which are outside the system boundary in this LCVA).

Hydroelectricity-Based Electricity (Fuel Cell Bus & Electric Trolley Bus)

Conventional hydroelectricity power generation with the use of large human-made reservoirs also resulted in extremely low life-cycle emissions. There is, however, emission of greenhouse gases from most natural water bodies, and an effort was made to quantify these amounts. The resulting life-cycle GHG emissions from a hydroelectricity-based fuel cell bus or electric trolley bus system were less than 3% of the base case in Ontario and effectively zero in British Columbia.

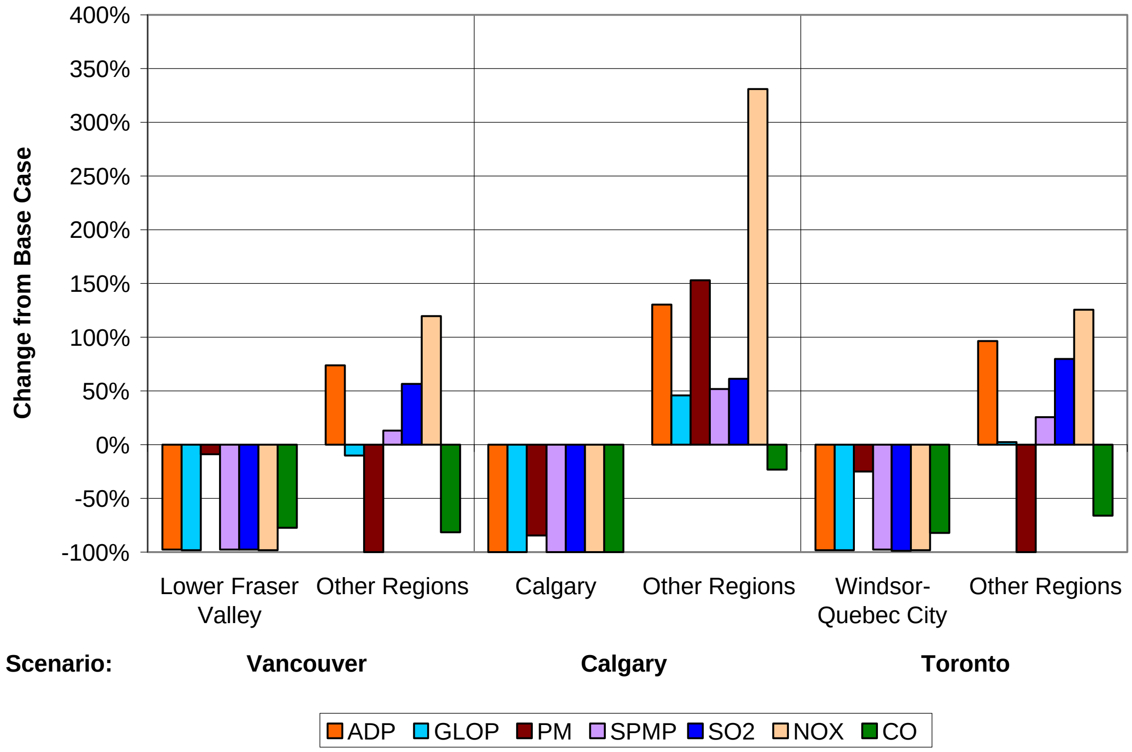
Nuclear Power–Based Electricity (Fuel Cell Bus & Electric Trolley Bus)

Nuclear power generation is another technology with very low life-cycle emissions. Even though uranium needs to be mined, transported and processed, the emissions per unit of electricity generated are very small because the amount of uranium required is small. In comparison with the base case, emissions from a nuclear power–based vehicle system in Toronto are nearly zero, with the exception of PM emissions from vehicle brake and tire wear. The stressor category with the next largest relative emission was sulphur dioxide, with less than 3% of the base case emissions.

Natural Gas–Based Electrolysis (Fuel Cell Bus)

Using natural gas power plants for hydrogen generation through electrolysis shifts nearly all air emissions away from the cities to the natural gas power plants and upstream natural gas supply system. In the Lower Fraser Valley, Calgary, and Windsor–Quebec City regions there is a very large decrease in all stressor categories compared with the diesel bus base case, as shown in Figure 5.16, except PM, which shows smaller decreases in both the Vancouver and Toronto scenarios due to natural gas–fired power plant emissions. Figure 5.16 also shows that there are some very large increases in criteria air contaminant emissions outside of the operating city regions owing to natural gas production and distribution, and, in the Calgary scenario, natural gas-fired power plant emissions. On a life-cycle basis, there is a decrease in every stressor category when compared with the base case (the majority of stressors decrease more than 40%), except for GHG and SO_2, which increase an average of 64% and 29% respectively for each of the three scenarios. The life-cycle performance of the fuel cell bus is expected to improve further as the technology matures.

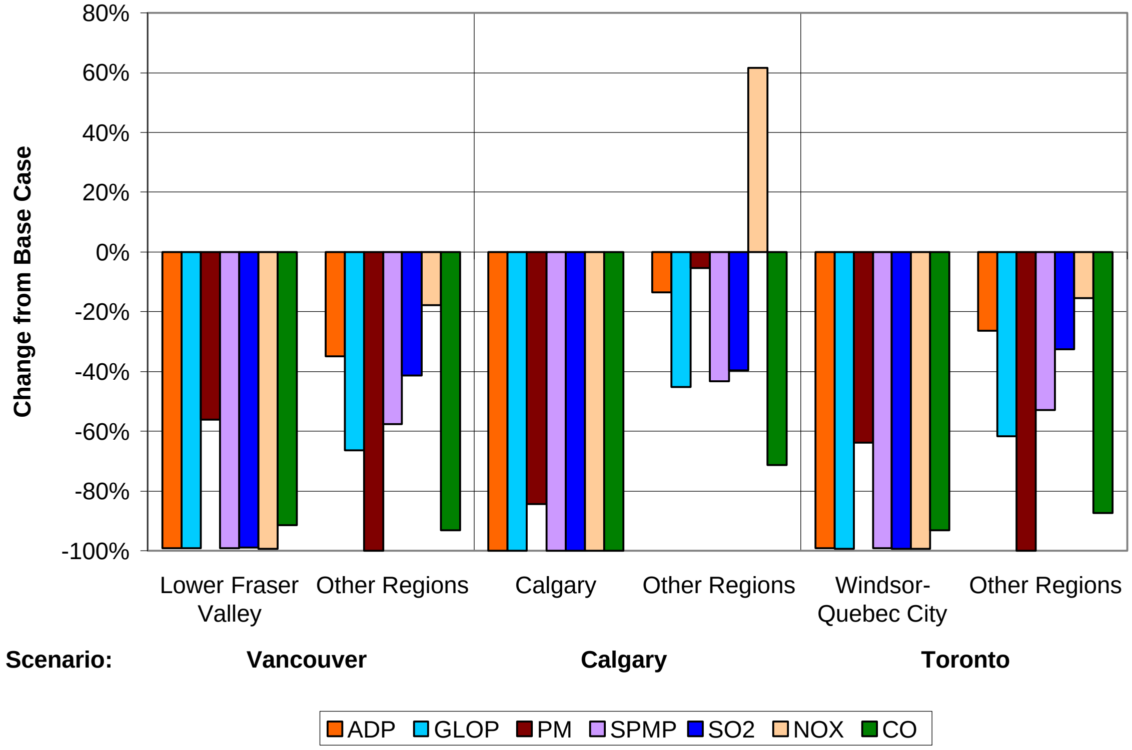
Figure 5.16 Change in Regional Emissions for FCVs Powered with Natural Gas–Based Electrolysis Compared with the Diesel Bus Base Case



Natural Gas–Based Electric Trolley Bus

The operation of an electric trolley bus powered by a natural gas–fired power plant offers a decrease, when compared with the diesel bus base case, in life-cycle emissions of at least 37% in all stressor categories including more than 82% reduction in ADP, GLOP, SPMP, NO_X and CO emissions, as shown in Figures ES.5 to ES.7. These large emission reductions occur mostly in the cities of bus operation, but they are also evident in all other regions for nearly all stressor categories, as shown in Figure 5.17. Similar to the light-duty vehicle scenarios, even with a net life-cycle reduction in pollutant emissions, the regions surrounding natural gas power plants will experience significant increases in pollutant releases, thus increasing environmental burden in those areas. Particular attention should be drawn to the increase in upstream NO_X emissions in the Calgary scenario, which is partly the result of not using selective catalytic reduction on the natural gas power plants.

Figure 5.17 Change in Regional Emissions for a Natural Gas–Powered Electric Trolley Bus Compared with the Diesel Bus Base Case



Coal-Based Electricity (Fuel Cell Bus & Electric Trolley Bus)

Like the light-duty vehicle scenarios, the fuel cell and electric trolley bus scenarios powered by coal-based electricity show very large increases in certain stressor categories, primarily PM and SO_2, compared with the diesel bus base case. This is shown in Figures ES.5 to ES.7. In general, these systems shift air emissions away from areas of vehicle operation, and crude oil production and refining, to areas of coal-fired power plants and coal mining. The result is a concentration of air pollutant emissions in these areas. Figures 5.18 and 5.19 show the regional results for the fuel cell and electric trolley bus scenarios respectively. For the NEBUS, most stressor categories are twice as great as the base case or higher, for both the life-cycle and the regions of electricity generation. For the electric trolley bus, the emissions increases are not as large, while some GLOP and NO_X emissions decrease as much as 76% on a life-cycle basis. However, the life-cycle emissions increase more than 180% in both the Calgary and Toronto scenarios for PM and SO_2. Once again, particulate matter has the largest increase in air pollutant emissions and occurs primarily in the areas of coal mining (particularly the northeastern U.S. Appalachian region) and electricity production.

Figure 5.18 Change in Regional Emissions for Fuel Cell Buses Powered with Coal-Based Electricity Compared with a Diesel Bus

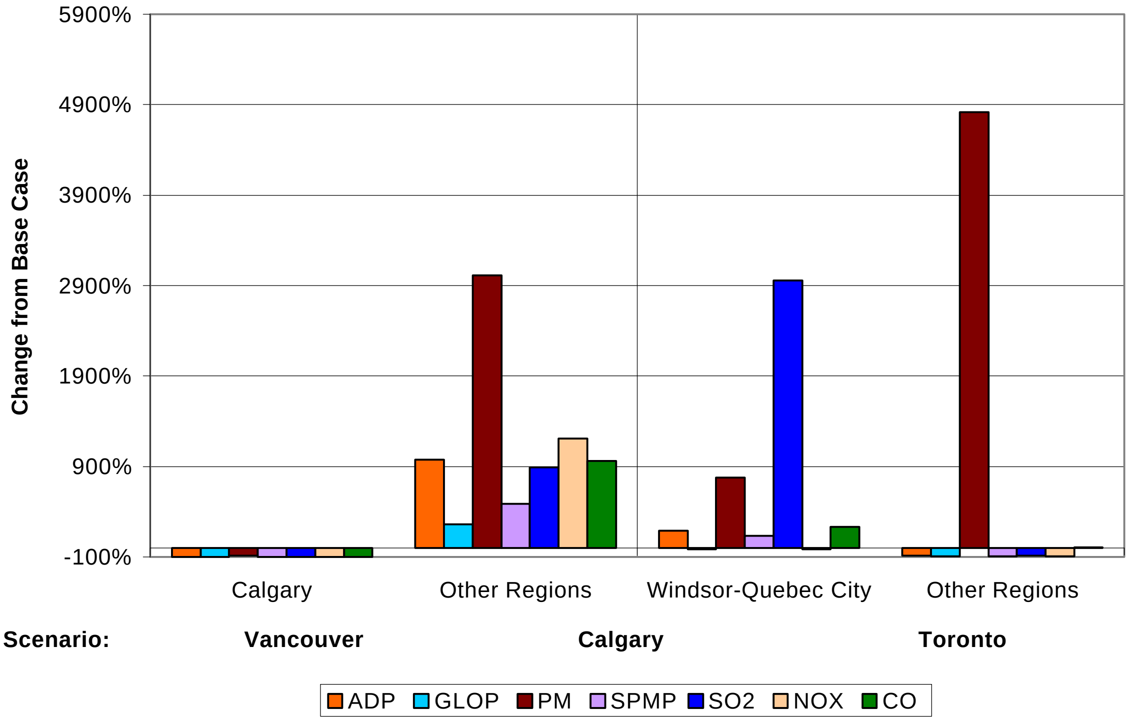
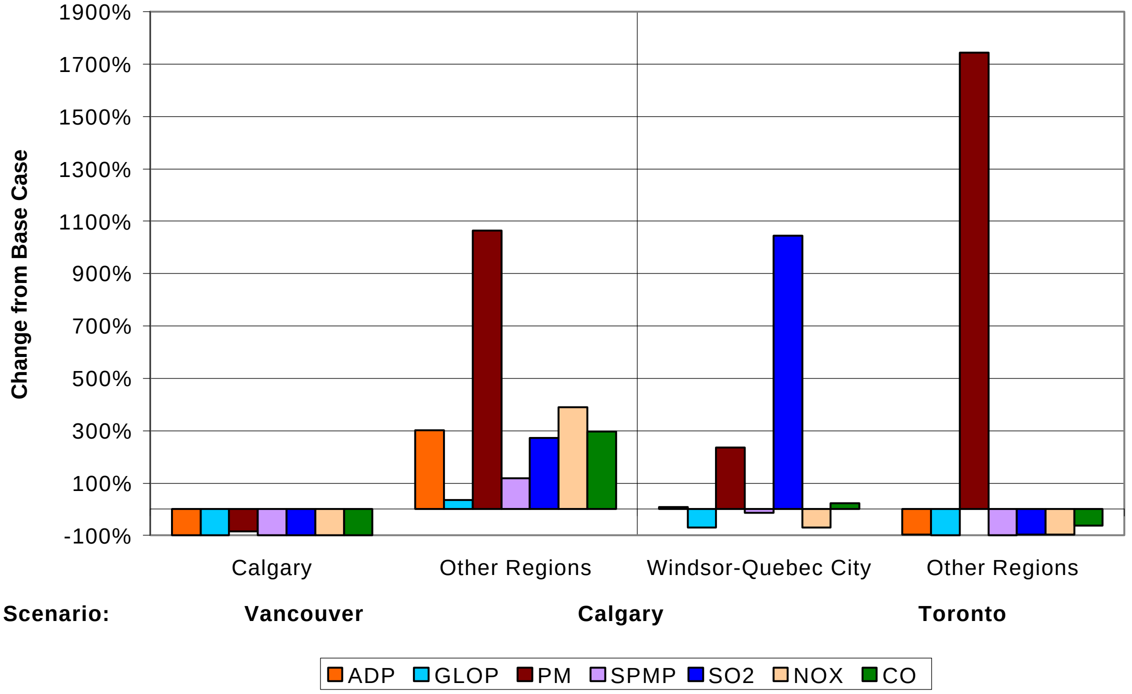


Figure 5.19 Change in Regional Emissions for Electric Trolley Buses Powered with Coal-Based Electricity Compared with a Diesel Bus



System Sensitivity Analysis

Over the course of the LCVA, many questions arose regarding the sensitivity of system results to the respective system assumptions. Four of these questions were investigated.

Opportunities for Emission Reductions

A sensitivity analysis was performed to identify areas where emission performance could be greatly improved through better system design. Generally speaking, since all of the systems flow in a fairly linear fashion, a reduction in fuel consumption or resource requirements proportionately decreases all upstream emissions. Therefore, the farther downstream the improved efficiency occurs, the more emission sources it will impact. Reducing the distance travelled would provide the greatest reduction in life-cycle emissions. The second best place to improve efficiency is at the point of the vehicle itself. Increasing the fuel efficiency of the vehicle would decrease all of the fuel production and distribution emissions proportionately (a major component of the life-cycle emissions in all the systems evaluated). Other unit processes (and their primary inputs) where efficiency increases can significantly decrease life-cycle emissions are the electrolysis of water (electricity), steam methane reforming of natural gas (natural gas and electricity), methanol production (natural gas), gasoline and diesel production (conventional and synthetic crude oil), recharging of electric vehicles (electricity), and hydrogen and natural gas compression (electricity).

The sensitivity analysis of potential areas of emission reductions also identified the level at which individual unit processes affected the life-cycle results. Table 5.1 is a listing of the largest emission source in each stressor category for the systems evaluated. In other words, these unit processes have the most potential to reduce life-cycle emissions in their respective systems through reductions in their own emissions. This does not indicate these areas are necessarily the easiest or most likely places to reduce emissions, nor are they necessarily significant emission sources when compared with other systems. A more thorough investigation into the specific transportation application, which includes technical feasibility and costs among other factors, must be done to properly assess where system design improvements can best be made to reduce life-cycle emissions.

Table 5.1 Primary Emissions Sources for Each System Evaluated

System	Unit Process	Stressor Categories
A & AA	Operate gasoline LDV	GHG, PM, CO
	Crude oil production	ADP, GLOP, SPMP, SO_2, NO_X
B	Operate diesel LDV & bus	GHG, ADP, GLOP, PM, SPMP (Bus only), NO_X, CO
	Crude oil production	SPMP, SO_2
C	Operate natural gas LDV	GHG, PM, CO
	Operate natural gas bus	GHG, ADP, GLOP, PM, SPMP, NO_X, CO
	Produce & process natural gas	ADP, GLOP, SPMP, SO_2, NO_X
D	Operate methanol FC LDV	GHG, PM
	Produce methanol	CO
	Produce & process natural gas	ADP, GLOP, SO_2, NO_X, SPMP
E & F	Operate FCV	PM
	Reform NG decentrally & centrally	GHG
	Produce & process natural gas	ADP, GLOP, SPMP, SO_2, NO_X
	Produce electricity from coal (Toronto scenarios)	CO, PM
	Mine coal (Toronto scenarios)	PM
I & N	Operate FCV or EV	PM
	Produce electricity from natural gas	GHG, PM, NO_X (Calgary only), CO
	Produce & process natural gas	ADP, GLOP, SPMP, SO_2, NO_X
J & O	Produce electricity from coal	GHG, ADP, GLOP, PM, SPMP, SO_2, NO_X, CO
	Mine coal (Toronto scenarios)	PM

Note: This list does not consider relative emission levels between systems. For example, FCVs and EVs may be a primary emission source for PM in Systems I and N owing to brake and tire wear, but this does not indicate the level of PM emissions compared with the base case scenarios. Systems G, H, K, L, M, P and Q have extremely low life-cycle emissions and were therefore not listed.

Oilsands Sensitivity

The first system sensitivity analyzed is the effect crude oil source has on the gasoline and diesel systems. The alternative source of crude oil evaluated is the oilsands of northeastern Alberta. This unit process was compared with the average production from the Western Canadian Sedimentary Basin, which is a combination of conventional oil production and oilsands production of synthetic crude oil (based on actual production volumes). The gasoline ICE LDV scenario for Calgary is used as the basis for comparison.

The results from the sensitivity analysis are shown in Table 5.2. The data used are specific to individual oilsands and refinery operations and may or may not be applicable to other operations. Data sources are listed in Appendix B: “Unit Process Descriptions.” Of the stressor categories where comparison is possible, ADP, GLOP, SPMP and SO_2 emissions are less for the oilsands case. This is driven mainly by the much lower VOC emissions associated with crude oil production from oilsands (0.22 kg/1000 km of LDV travel) and the lower SO_2 emissions from both crude oil production (0.06 kg/1000 km) and refining (0.06 kg / 1000 km). Conversely, both NO_X and GHG emissions increase when compared with the base case. This is a result of the higher energy requirements of crude oil production from oilsands (0.09 kg NO_2 and 18 kg CO_{2eq}. / 1000 km) and refining (5 kg CO_{2eq} / 1000 km).

Table 5.2 Oilsands Sensitivity Results for Scenario 20 – Gasoline ICE LDV in Calgary

Stressor Category	Units	Base Case - WCSB Average Crude Oil	Sensitivity - Oilsands Synthetic Crude Oil	Difference
GHG	kg CO2eq	204	225	10%
ADP	kg SO_2eq	0.43	0.37	-14%
GLOP	kg	0.70	0.61	-13%
PM	kg	0.02	I/D	I/D
SPMP	kg	0.98	0.76	-26%
SO_2	kg	0.34	0.23	-30%
NO_X	kg	0.20	0.28	44%
CO	kg	0.24	I/D	I/D

I/D – insufficient data

Liquid Hydrogen Sensitivity

The second system sensitivity analyzed is the effect hydrogen liquefaction has on the centralized SMR-based FCV systems. In this case, hydrogen is liquefied at the centralized SMR plant, transported via tanker truck, and stored in liquid form at the plant site, refuelling station and on board the FCV. DaimlerChrysler's NECAR 4 (liquid hydrogen) and 4a (gaseous hydrogen) have been used in the analysis. It is assumed that they have equivalent fuel consumption performance.

Table 5.3 shows the results of the liquid hydrogen sensitivity analysis. The liquid hydrogen scenarios require 5.4 times more electricity than the gaseous hydrogen scenarios. The difference is primarily caused by the higher energy requirement of hydrogen liquefaction compared with compression to 700 bar. In the Calgary scenarios, where electricity is supplied primarily by coal-fired power plants, using liquid hydrogen instead of gaseous hydrogen for FCVs increases the life-cycle emissions of every stressor category investigated by more than 60%. In Vancouver, where electricity is supplied primarily by hydroelectricity, liquid hydrogen results in a much smaller increase in life-cycle air emissions compared with gaseous hydrogen. Most of the stressor categories increase only 1%, although carbon monoxide emissions increase by 9%. This is a result of the increased demand for natural gas–based electricity and appears disproportionately large because of the relatively low CO emissions throughout the rest of the life cycle.

Table 5.3 Liquid Hydrogen Sensitivity Results – Centralized SMR-Based Fuel Cell LDV

Stressor Category	Units	Calgary			Vancouver		
		Base Case Gaseous H2	Sensitivity Liquid H2	Difference	Base Case Gaseous H2	Sensitivity Liquid H2	Difference
GHG	kg CO2eq	156	255	64%	134	136	1%
ADP	kg SO2eq	0.34	0.74	118%	0.25	0.25	1%
GLOP	kg	0.21	0.39	89%	0.18	0.18	1%
PM	kg	0.018	0.035	97%	0.013	0.013	1%
SPMP	kg	0.438	0.90	105%	0.34	0.34	1%
SO2	kg	0.23	0.50	119%	0.16	0.16	1%
NOx	kg	0.16	0.34	114%	0.13	0.13	1%
CO	kg	0.032	0.12	293%	0.0073	0.0080	9%

Grid Average Electricity Sensitivity

If grid average electricity is to be used for either FCVs or EVs, a weighted average of the life-cycle results can be used to estimate the air pollutant emissions from this type of system. With a high percentage of power coming from coal, Alberta would not be a likely candidate for this type of transportation system. British Columbia, on the other hand, would have a large reduction in air pollutant emissions from an electricity-based transportation system. The capacity of the current hydroelectricity system would limit the amount of low-emission electricity available for transportation.

5.5.3 Resource Consumption

Any resource consumption that occurs during the life cycle of vehicle operation limits the quantity of resources available within the physical environment. Whether they are renewable or non-renewable, the resources consumed are not available for other uses. In the case of renewable resources, such as water, there is a finite amount available at any given time for industrial, agricultural and personal use, as well as for use within the natural environment to maintain the health of the ecosystem. In the case of non-renewable resources, although no major shortages are forecast for the foreseeable future, supply is ultimately limited.

Figures 5.20 to 5.25 summarize the amount of primary energy resources consumed in each scenario assessed. The energy values used for hydroelectricity, wind power and uranium are not equivalent to the higher heating values used for the hydrocarbon energy sources. The energy consumption shown for hydroelectricity and wind power are the amount of electricity consumed and do not represent the full potential of the water and wind resources. The energy value for uranium is a factor used by Natural Resources Canada (NRCan 1997) to estimate the typical amount of heat energy obtained from uranium for the generation of electricity from nuclear power plants in Canada (11.6 MJ of heat used to generate each kWh of electricity). The energy content of hydrocarbon energy sources on the other hand represents the theoretical maximum amount of energy that is released through combustion. This is not an entirely equitable basis for comparing the efficiencies of each system since the inefficiencies of generating electricity from hydroelectric and wind resources, and heat from uranium fuel are not taken into account. This analysis does, however, give an indication of the level of primary energy resources required for the operation of each vehicle type.

A trade-off must be made when comparing different systems. One combination of resources will need to be used instead of another. Ultimately, it will be the system designers and operators that will need to choose the amount and type of resource to consume. The information presented in this section can assist in comparing the life-cycle requirements for each unique vehicle and fuel supply combination in a particular region of the country.

The gasoline Focus system requires the highest amount of primary energy of the ICEVs analyzed. This is due to the high fuel consumption and energy-intensiveness of gasoline production. Both the diesel Jetta system and the Prius HEV system benefit from higher vehicle efficiencies than the gasoline Focus, and correspondingly lower primary energy consumption. The natural gas Civic has, on average, 41% fewer primary energy requirements than the gasoline Focus system due to a more efficient vehicle platform and lower energy requirements for fuel production. Conversely, the natural gas bus is not as efficient as the diesel bus, resulting in an 8% increase in energy consumption on average.

The primary energy consumption for the NECAR 5 methanol FCV system is 9% lower than the gasoline Focus base case, primarily due to an inherently more efficient vehicle technology. As mentioned previously, a further 17% reduction in methanol and primary resource consumption is expected due to weight optimization of the NECAR 5. Further reductions may be possible through technology advancements.

The primary energy consumption for both the centralized and decentralized SMR systems are demonstrated to be very similar, but both vary depending on the source of electricity within the scenarios. Electricity generation makes up between 4% and 22% of the system’s energy consumption. For the NECAR 4a, the decentralized SMR scenarios range between 29% and 40% less than the gasoline Focus scenarios owing to the efficiency of FCVs. For buses, the primary energy consumption of the NEBUS is comparable to the diesel ICE base case, ranging from 15% greater to 3% less. The life-cycle energy consumption of fuel cell vehicles is expected to decrease as the technology matures.

The non-renewable energy-based electrolysis systems have the highest primary energy consumption of all the systems analyzed. Nuclear power plants use the most primary energy, closely followed by conventional coal-fired power plants. Combined-cycle natural gas power plants demonstrate their high efficiency benefits, as they have much lower energy requirements than the other power generation options, but still remain higher than all of the non-electrolysis systems. The renewable energy-based electrolysis systems (hydroelectricity and wind power) consume an average of 640 kWh per 1000 km of LDV travel and 7,700 kWh per 1000 km of bus travel.

For the electric vehicle systems, the nuclear and coal-based scenarios all consume close to the same amount of primary energy as the diesel ICE scenarios, with some variations. The natural gas–based EV scenarios are the lowest energy consumers of fossil fuel–based systems. The renewable energy–based electric vehicle systems (hydroelectricity and wind power) have the lowest energy consumption of all the systems, consuming an average of 220 kWh per 1000 km of LDV travel and 2,900 kWh per 1000 km of bus travel.

Water use within the systems was identified as another major depletion of resources within the operation of almost every vehicle / fuel supply system. Operations with major water requirements include power plants, steam methane reformers, oil and gas fields, oilsands operations, refineries, natural gas plants and electrolysis units.

Figure 5.20 Energy Consumption for Vancouver LDV Scenarios

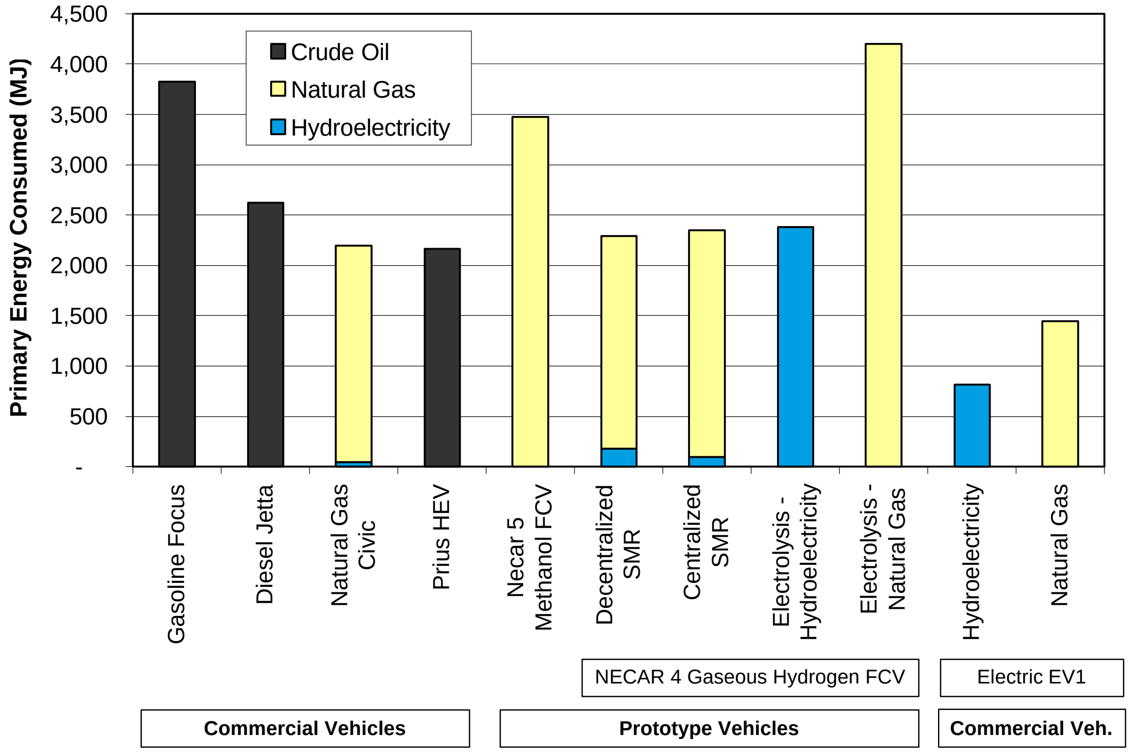


Figure 5.21 Energy Consumption for Vancouver Bus Scenarios

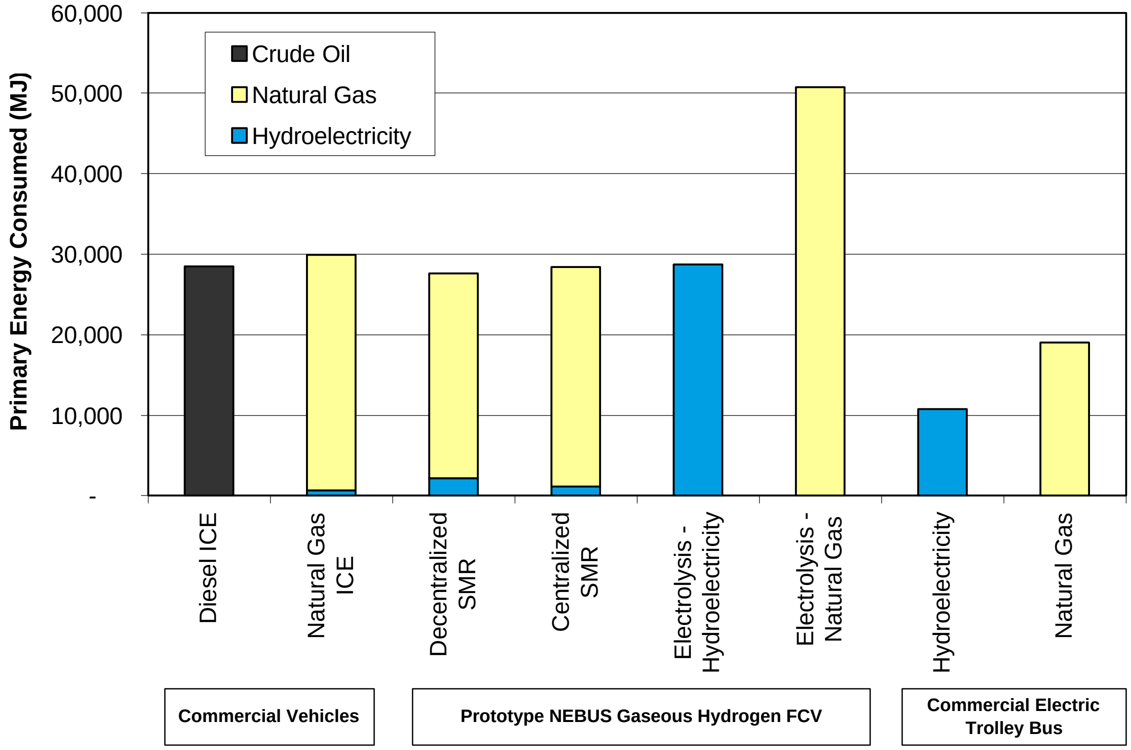


Figure 5.22 Energy Consumption for Calgary LDV Scenarios

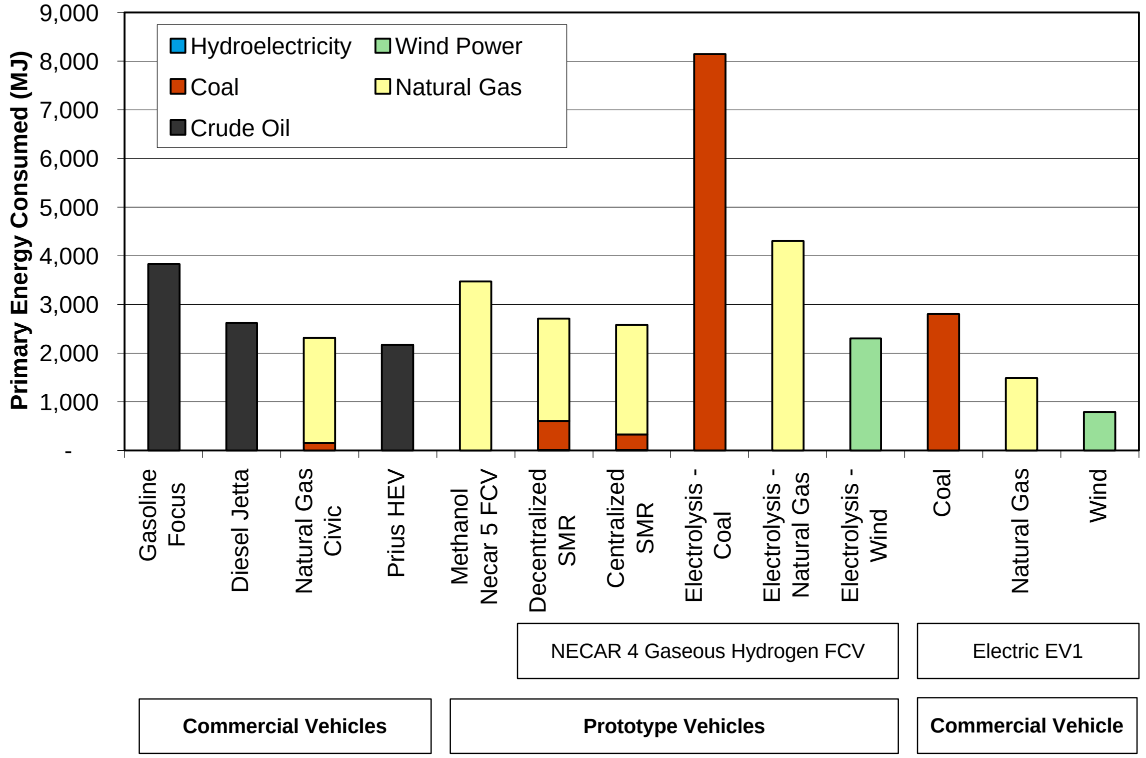


Figure 5.23 Energy Consumption for Calgary Bus Scenarios

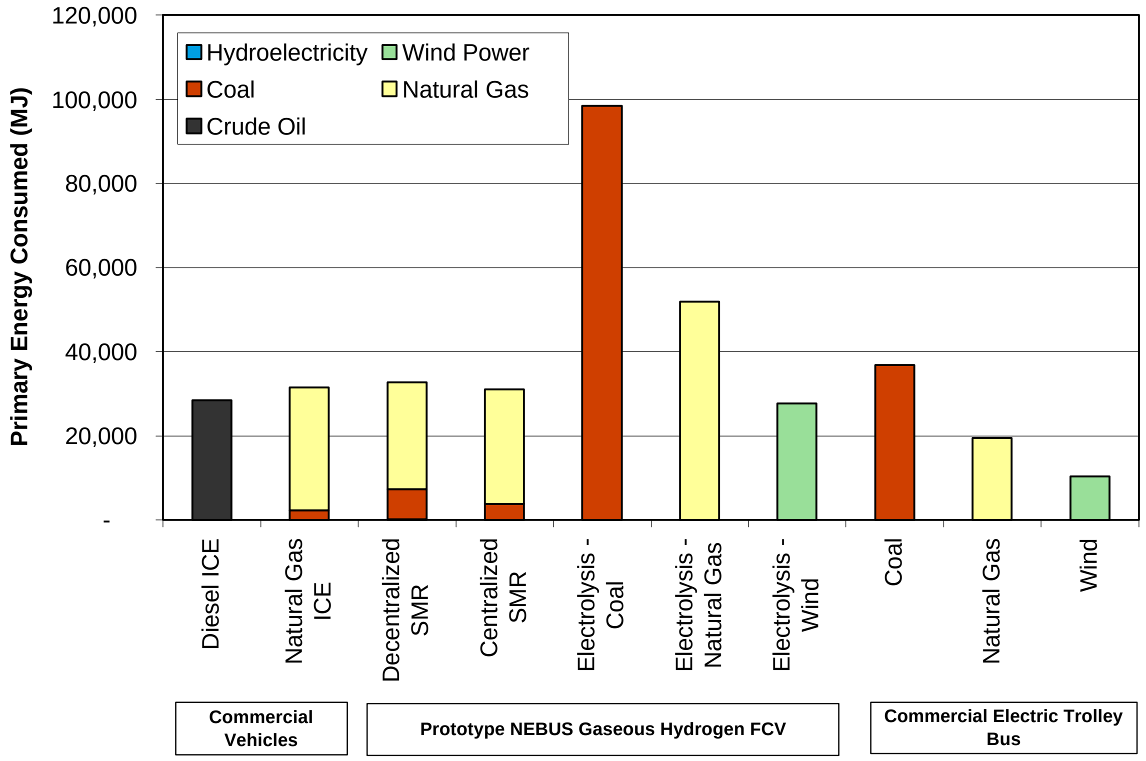


Figure 5.24 Energy Consumption for Toronto LDV Scenarios

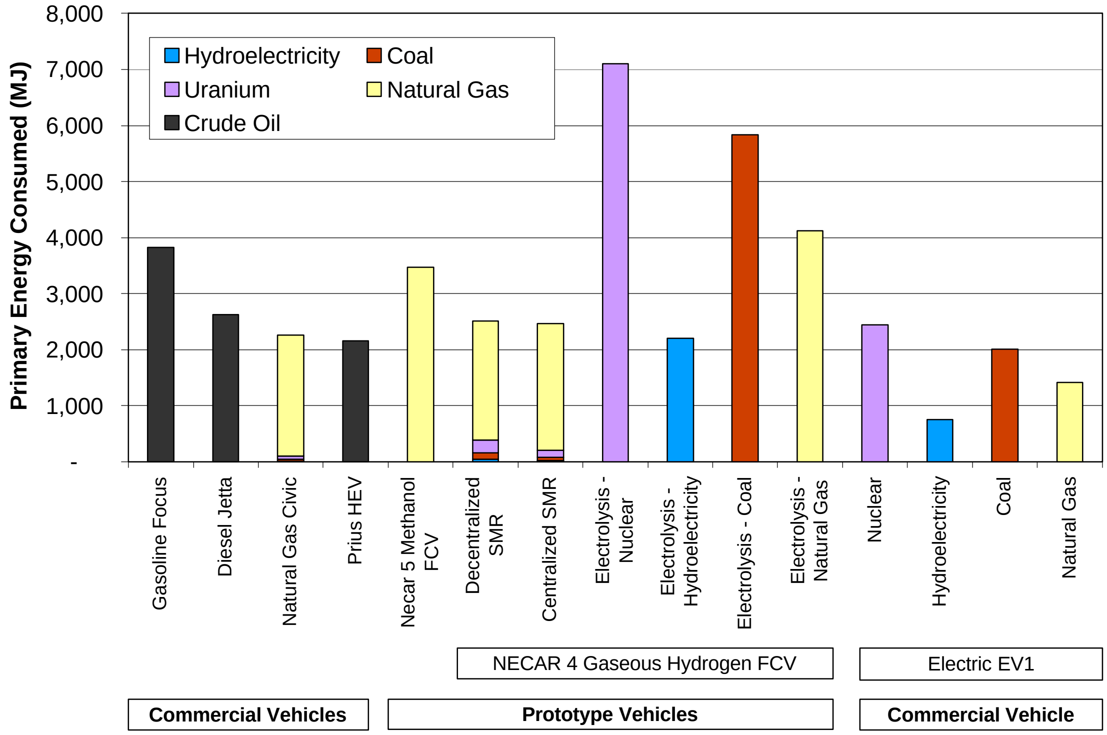
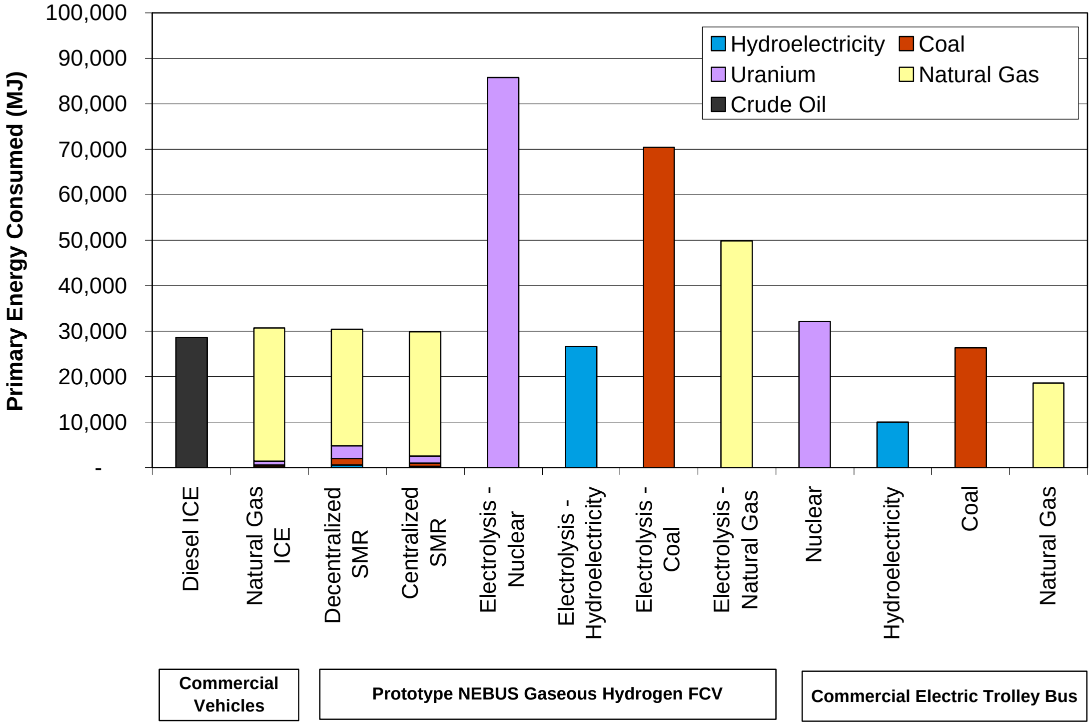


Figure 5.25 Energy Consumption for Toronto Bus Scenarios



5.6 Other Environmental Stressors

During the scoping process a number of additional environmental stressors were identified. A list of these stressors appears below along with a brief description of the context of each one. Table 5.4, at the end of Section 5, summarizes these stressors and identifies the specific systems to which they apply. These stressors have been listed for the purpose of providing a broader perspective to the analysis and for identifying areas requiring additional research.

5.6.1 Other Air Pollutants

In addition to the criteria air pollutants recorded earlier in this report there are a growing number of other air pollutants under investigation with respect to the effects they have on human health and the environment. The Canadian federal government has considered evaluating 67 chemicals on their "critical pollutants" list, which includes benzene, and various polycyclic aromatic hydrocarbons (PAHs) that are components of vehicle exhaust emissions.

Fuel Combustion Emissions

Pollutants that are emitted from vehicles, power plants and pipeline compressors or pumps are unique to the type of fuel combusted. In general, the more complex the fossil fuel, the more complex and varied are the emissions. The effects of exposure to the listed pollutants range from irritation of eyes, nose and throat to organ disease and cancer depending on the specific pollutant and the level of exposure.

Gasoline

Gasoline is a liquid mixture of several hundred types of complex hydrocarbons. Most of the hydrocarbons contain four to twelve carbon atoms. Gasoline is produced from the refining of crude oil and is primarily composed of 3 classes of hydrocarbons: paraffins (60%), aromatics (30%) and olefins (10%) (Webb 1993). Emissions from gasoline-powered vehicles include known or probable human carcinogens, including benzene, formaldehyde, acetaldehyde and 1,3-butadiene. Non-hydrocarbon components (oxygenates and heavy metals) of gasoline that can comprise up to 13% of gasoline by weight (U.S. Dept. of Health & Human Services 1993).

Diesel

Diesel fuel is a complex liquid mixture of hydrocarbons, with a higher number of carbon atoms than that of gasoline. It is produced from the refining of crude oil and like gasoline, is primarily composed of 3 classes of hydrocarbons: paraffins (71%), aromatics (28%) and olefins (1%) (Webb 1993). Speciated exhaust components of diesel exhaust include: benzene, 1,3 butadiene, formaldehyde, acetaldehyde, polyaromatic hydrocarbons (PAHs) and nitro-polycyclic aromatic hydrocarbons (N-PAHs) (Unnasch 2000). Non-hydrocarbon components (oxygenates and heavy metals) are also present in diesel fuel.

Methanol

Methanol, also known as wood alcohol (used to be derived from the destructive distillation of wood), is a liquid created from a synthesis gas (hydrogen and CO), which is reacted in the presence of a catalyst. In general, most of the world's methanol is produced by a process using natural gas as a feedstock. Methanol can also be produced from nonpetroleum feedstocks such as coal and biomass (California Energy Commission web site 1999). Methanol was not combusted within the system investigated in this LCVA. However, if methanol is combusted, the primary hydrocarbon emission constituents are formaldehyde and methanol (Baird 1993a). Testing completed by DaimlerChrysler and Ballard did not detect any formaldehyde emissions from the NECAR 5 methanol fuel cell vehicle.

Natural Gas

Natural gas is a gaseous fossil fuel, often found in the same geologic formations as petroleum. It can also be produced as a "by-product" of landfill operations (California Energy Commission web site 1999). Composed primarily of methane (85-99% CH_4 by volume), retail sales composition varies due to various upstream handling issues (geologic formation, supply and gathering line mixing) would also include small volumes of ethane, propane, nitrogen, carbon dioxide (from 1 to 3% by volume each) and very small proportions of butane, pentane derivatives (less than 1/10 of 1 percent each) (Union Gas 2002). Natural gas emits no evaporative emissions (VOCs) during fuelling and use, which can account for at least 50 percent of a gasoline vehicle's total hydrocarbon emissions (California Energy Commission web site 1999). However, formaldehyde is a component of its combustion emissions (Unnasch 2000).

Hydrogen

Hydrogen is a gas that can be produced from a number of different resources, including natural gas, water and methanol. Hydrogen was not combusted within the systems investigated within this LCVA; however, when hydrogen is combusted, nitrogen oxides are the only pollutants produced.

Coal

Coal is a combustible, black sedimentary rock composed predominantly of carbon. It is formed out of plant matter that accumulated at the bottom of swamps millions of years ago, during the Carboniferous Period. It contains contaminants related to its geographic location. When coal is burned to produce electricity, these source contaminants are either retained in the ash product of combustion, retained partially in the ash byproduct of combustion or primarily emitted to the atmosphere. Contaminants can vary in quantity from being only in trace amounts, to non existent, to varying percentages of the total volume. For example, a study done in Spain indicated that the elements Ba, Ce, Co, Cs, Cu, Dy, Ga, Ge, La, Lu, Mn, Ni, Rb, Sr, Tb, Th, Y, Yb, Zn and Zr are retained in the solid wastes after combustion; As, B, Be, Cd, Cr, Li, Mo, Pb, Sb, Sn, Ta, Tl, U, V and W were only partially retained in the solid wastes; and Hg and Se were primarily emitted to the atmosphere (Llorens 2001). It is of note that the elements and radioactive components in the coal and flyash waste are not of an enriched concentration enough to cause alarm (Central Energy Resources Team 1997). When these elements are released into the environment, they may pose a serious hazard to people and wildlife. As an example, mercury (Hg) is mobile, persistent and bioaccumulative.

Oil & Gas Well Venting

Gas is regularly vented and leaked from oil & gas wells and can have a dramatic effect on air quality in the immediate vicinity. The risk of exposure to hydrogen sulphide (H_2S) from release of “sour” gas is the most significant public safety hazard associated with oil and gas drilling. Hydrogen sulphide is acutely toxic to humans starting at very low levels of exposure. A concentration of 10 parts per million can start to cause eye irritation (State of Michigan Dept. of Environmental Quality 2002), with death occurring within a few minutes at levels of 1000 ppm or greater (Guidotti 1996). Other common pollutants related to oil and gas wellsite facilities are benzene, toluene, ethylbenzene and xylene, from glycol dehydrator systems, and many of the emissions mentioned earlier tied to the operation of gasoline, diesel and natural gas combustion engines.

5.6.2 Water-Body, Groundwater and Sewer Pollutants

Release of liquid pollutants into local water bodies, groundwater and sewers is a concern, especially when assessing a fuel infrastructure that deals with liquid fuels. There are many points along the resource development, fuel production, and supply chain where liquids may be spilled, leaked or disposed of into the environment. In some locations, such as refineries and central storage facilities, large amounts of potential pollutants are stored, but in a more controlled environment. Releases from other locations, such as tanker trucks and on-board individual vehicles, may be more likely but the overall volumes are usually smaller. Occasionally, spills occur in the upstream oil and gas industry that prove to be nearly catastrophic for the local environment. For example, spills from large oil tanker ships can have a devastating impact on marine and shore life. The following are some potential liquid contaminants:

- gasoline
- diesel
- methanol
- motor oil
- automotive coolant
- refinery chemicals and byproducts
- water effluents from power plants
- crude oil
- drilling rig chemicals

These liquids have the potential to be released into the environment through a number of methods, including both intentional and accidental release during production; transportation via pipeline, rail or truck; above-ground and underground storage; transfer between storage points, use and disposal. The specific environmental impact of each liquid was not investigated; however, Section 6.2.1 provides a general discussion of the safety characteristics of the fuels considered in this study.

5.6.3 Wildlife and Plant Life Disturbance, Habitat Fragmentation and Biodiversity Impacts

The preservation of wilderness areas is of importance to governments and the public, however, it is often at odds with the development of natural resources. The operation of industry within these areas can have a significant impact on the ability of plants and animals to survive. There are several ways in which industry can affect plant and animal life: disturbance from existing and established locations, habitat fragmentation which limits the overall land area that is available to wildlife, limiting biodiversity which affects the overall ecosystem’s health and ability to adapt to change. Some industrial activities that have an impact upon wilderness areas are:

- hydroelectricity reservoirs including upstream and downstream areas,
- oil and gas exploration,
- coal, oilsands and uranium mining,
- pipelines,
- electricity transmission lines, and
- roads and railways, along with their associated traffic.

5.6.4 Solid Waste

The disposal of solid waste is becoming increasingly difficult. High disposal standards and costs are progressively being implemented for hazardous wastes, chemicals and oils. Many municipalities are also having difficulties finding locations for new landfills. Increasingly, governments are encouraging companies and individuals to reduce the amount of waste they generate.

For the vehicles compared in this study, most of the components are very similar (with the exception of the drivetrain) and therefore will generate similar solid waste, with some exceptions. Batteries used in the electric and hybrid electric vehicles may need to be replaced one or more times during the life of the vehicle and will require special disposal. One common waste product that is continually being generated by vehicles with combustion engines is the oil filter, which also requires special disposal.

The fuel supply chain will also produce its own share of solid waste. The operation and maintenance of industrial facilities, transport infrastructure, and resource extraction operations are just a few examples.

5.6.5 Radioactive Waste

Radioactive material can be dangerous to any living thing: plants, animals and humans (Brain 2001). High doses of radiation pose serious health risks with both somatic and genetic effects. The somatic effects include cell death, an increased risk of cancer, and a reduction in length of life; genetic effects alter the genetic structure and can be passed on to offspring (University of Missouri-Rolla American Nuclear Society 2002). The threshold level of radiation is a controversial issue. Some studies argue that small doses of radiation are actually healthy and others argue that no level of radiation is acceptable. Several studies have claimed to discover higher levels of some cancers such as leukemia, and birth defects in those living near nuclear power plants; but more study is needed in this area (Baird 1993b).

The radioactive wastes that are generated from nuclear power plants can be classified into two general categories: high-level waste (HLW) and low-level waste (LLW). High-level waste consists of spent reactor fuel in either solid or liquid form and is expected to be radioactive for thousands of years. Low-level waste, on the other hand, carries a relatively small amount of radiation in a large amount of material (Platts Global Energy web site 2001b).

High-level waste requires temporary storage in heavily shielded cooling ponds or vaults on the plant site for 10 to 15 years prior to disposal, to allow both the temperature and the radioactivity of the material to decrease. In Canada, some of the high-level waste has been moved from wet storage to dry storage with air-cooling. Currently, there is no other disposal method in use in Canada.

To adequately dispose of high-level waste it must be isolated for thousands of years until the radiation levels have been reduced to an acceptable standard (NEA web site 2002). The disposal options include deep geological storage, disposal under the ocean floor, disposal into glaciated areas, disposal into space, and destruction by nuclear transmutation, but their effectiveness is not entirely understood owing to the length of time required for storage. One proposed central waste disposal site for Canada is underground in the Canadian Shield. This method of disposal runs the risk of contaminating groundwater with radioactive material. The groundwater flow eventually will reach the surface and enter the food chain. Earthquakes and other seismic movement are also a danger to the proper containment of the waste. Fracturing during excavation, human intervention, or heat generated by the waste are other causes for leakage. Experience in Canada and around the world shows that it will be extremely difficult and time-consuming to locate and approve any disposal sites for HLW (CNP 2002).

Low-level waste in Canada is a combination of historic waste such as contaminated soil from past processes and ongoing waste such as “dirty” material from nuclear power plants. The waste contains a small amount of radiation with a large amount of material. LLW is stored in interim storage facilities waiting permanent disposal. There is currently no official federal government action for long term LLW disposal in Canada (Platts Global Energy web site 2001a).

Mining uranium releases radiation into the environment and results in large volumes of radioactive mine tailings. Processing the uranium into fuel for reactors can also result in low-level radioactive contamination, as can reactor operation and fuel disposal.

5.6.6 Land Use

The amount of land used by resource development, industrial facilities, and urban development reduces the amount of land that contributes both to the health of the ecosystem and the lifestyle of the people, plants and animals who use it. This is an increasing issue in cities where urban sprawl is reducing the amount of green space, agricultural land, wildlife and air quality. Similarly, large industrial and resource development projects can completely alter the landscape of a rural region. The impact can be widely felt by those who rely on the land for work, recreation, habitation, food, spiritual purposes, access to adjacent areas, or many other activities. Below is a list of factors that affect the use of land within the systems assessed.

- hydroelectricity reservoirs
- coal, oilsands and uranium mines
- oil and gas wells and production facilities
- electricity transmission and distribution lines
- oil, gas and oil product pipelines
- centralized SMR plant
- power plants
- wind farms
- oil refineries
- fuelling stations
- waste disposal sites
- roads for access to remote sites
- electric power cables over existing city roadways for trolley bus operation

It is beyond the scope of this study to quantify the land use impact in each system; however, since the above list constitutes several large-scale land use operations, further investigation is warranted.

5.6.7 Land, Water-Body and Underground Formation Disturbance

Temporary disturbance of land, water bodies and underground formations, including water aquifers, permanently alters them. This alteration occurs on a large scale through the extraction of fossil fuels. Oil and gas wells, as well as mining operations, can disturb the natural environment for many years. Currently in Canada there is a requirement for these industries to minimize their permanent impact on the land, surface water bodies, and underground formations; however, productivity may not be returned to these areas for many years, or it may be permanently lost.

Table 5.4 Summary of Qualitative Environmental Stressors Broken Down by System

System	A	AA	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
	Gasoli ne ICE	Gasoline HEV	Diesel ICE	NGV	Methanol FCV	H_2FCV - SMR Decentralized	H2 FCV - SMR Centralized	H_2FCV - Nuclear Electrolysis	H_2FCV - Hydro. Electrolysis	H_2FCV - Coal Electrolysis	H_2FCV - NG Electrolysis	H_2FCV - Wind Electrolysis	EV - Nuclear	EV - Hydroelectricity	EV - Coal	EV - Natural Gas	EV - Wind
Other Air pollutants																	
Vehicles	X	X	X	X	X												
Power plants				X		X	X			X	X				X	X	
Oil and gas well venting	X	X	X	X	X	X	X				X					X	
Resource extraction	X	X	X	X	X	X	X	X		X	X		X		X	X	
Water-body, Groundwater and Sewer Pollutants																	
Crude oil	X	X	X														
Gasoline	X	X															
Diesel			X														
Methanol					X												
Refinery chemicals and byproducts	X	X	X														
Automotive coolant	X	X	X	X	X	X	X	X	X	X	X	X					
Motor oil	X	X	X	X													
Water effluents from power plants				X		X	X	X		X	X		X		X	X	
Drilling rig chemicals	X	X	X	X	X	X	X				X					X	

Table 5.4 Summary of Qualitative Environmental Stressors Broken Down by System (continued)

System	A	AA	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
	Gasoline ICE	Gasoline HEV	Diesel ICE	NGV	Methanol FCV	H_2FCV - SMR Decentralized	H2 FCV - SMR Centralized	H_2FCV - Nuclear Electrolysis	H_2FCV - Hydro. Electrolysis	H_2FCV - Coal Electrolysis	H_2FCV - NG Electrolysis	H_2FCV - Wind Electrolysis	EV - Nuclear	EV - Hydroelectricity	EV - Coal	EV - Natural Gas	EV - Wind
Wildlife and Plantlife Disturbance, Habitat Fragmentation, and Biodiversity Impacts																	
Hydroelectricity reservoirs				BC, ON		BC, ON	BC, ON		X					X			
Oil and gas exploration	X	X	X	X	X	X	X				X					X	
Coal, oilsands or uranium mining	X	X	X	AB, ON		AB, ON	AB, ON	X		X			X		X		
Pipelines	X	X	X	X	X	X	X				X					X	
Electricity transmission lines				X		X	X	X	X	X	X	X	X	X	X	X	X
Road and rail traffic	X	X	X	X	incr.	X		X	X	X	X	X	X	X	X	X	X
Solid waste																	
Battery disposal		X											X	X	X	X	X
Oil filter	X	X	X	X													
Facility operation	X	X	X	X	X	X	X	X		X	X		X		X	X	
Resource extraction	X	X	X	X	X	X	X	X		X	X		X		X	X	
Ash from coal plants				AB, ON		AB, ON	AB, ON			X					X		
Radioactive waste																	
Nuclear power plant				ON		ON	ON	X					X				
Uranium mining				ON		ON	ON	X					X				

Table 5.4 Summary of Qualitative Environmental Stressors Broken Down by System (continued)

System	A	AA	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
	Gasoline ICE	Gasoline HEV	Diesel ICE	NGV	Methanol FCV	H$_2$FCV - SMR Decentralized	H2 FCV - SMR Centralized	H$_2$FCV - Nuclear Electrolysis	H$_2$FCV - Hydro. Electrolysis	H$_2$FCV - Coal Electrolysis	H$_2$FCV - NG Electrolysis	H$_2$FCV - Wind Electrolysis	EV - Nuclear	EV - Hydroelectricity	EV - Coal	EV - Natural Gas	EV - Wind
Land use																	
Hydroelectricity reservoirs									X					X			
Coal, oilsands or uranium mines	X	X	X	AB, ON		AB, ON	AB, ON	X		X			X		X		
Pipelines	X	X	X	X	X	X	X				X					X	
Electricity transmission lines				X		X	X	X	X	X	X	X	X	X	X	X	X
Central SMR plant							X										
Power plants				X		X	X	X		X	X		X		X	X	
Oil refineries	X	X	X														
Gaseous fuels at fuelling stations				X		X	X	X	X	X	X	X					
Waste disposal sites	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Roads for access to remote resource extraction	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Electric cables over existing roadways (bus only)													X	X	X	X	X
Land and Water Aquifer Disturbance																	
Coal, oilsands or uranium mining	X	X	X	AB, ON		AB, ON	AB, ON	X		X			X		X		
Oil and gas exploration,	X	X	X	X	X	X	X				X					X	

6 Social Considerations

Social issues and values influence consumer and societal acceptance of any product. The overall impact of a product or service occurs throughout its life-cycle and it is important for a producer to realize how these impacts will affect consumer decisions. Social considerations may become important factors in the success of the transportation alternatives considered here.

During the project's scoping exercise, a list of social considerations was compiled; it is presented below. Table 6.3, at the end of Section 6, summarizes the bulk of these issues and identifies the specific systems for which they apply.

6.1 Consumer Expectations and Needs

It is the consumer that makes the ultimate choice when it comes down to the market acceptance of a new technology. For new vehicle technologies, two key areas were identified that require consumer acceptance: vehicle performance and refuelling. Technology developers must consider all of the consumer's wants and needs when designing a product if they are to be successful.

6.1.1 Vehicle Performance

Overall, if a vehicle is to be accepted by the consumer, whether it is a light-duty vehicle or a bus, it must satisfy the basic requirements of the user. Comfort, range, storage capacity, acceleration, reliability and safety are a few factors that have been identified through the LCVA scoping process. Comfort encompasses many vehicle features, including passenger space, ride comfort, noise, convenience, and all of the many convenience or entertainment features often added to vehicles. Table 6.1 rates a number of performance criteria for the light-duty vehicles studied as they compare with gasoline vehicles.

Fuel storage requirements may be of particular concern to vehicles using gaseous fuels and batteries. These vehicles may need to compromise on the shape and volume of space available for passengers or cargo because the fuel tank volume required for an acceptable range may be larger than that required for a conventional liquid fuel tank. Currently, vehicles using gaseous or chemical (battery) fuel storage have a much lower range than conventional vehicles with liquid fuel storage. Some fuel cell vehicle designs have shown, however, that compressed hydrogen even at 350 bar (5000 psi) can be packaged into a slightly modified 5-passenger vehicle without intruding into the trunk or passenger space, while providing over 600 km range. Current prototype FCVs using compressed hydrogen, including the NECAR 4a, have not been designed to provide long range. The estimated range of the vehicles evaluated in this study is shown in Table 4.1.

It has also been demonstrated that vehicles powered by electric motors have several inherent benefits over conventional IC engines. The GM EV1 electric vehicle has the ability to accelerate faster than an equivalent gasoline car. Also, it is claimed by many electric and fuel cell vehicle proponents that these vehicles will require less maintenance and will be more reliable than ICEVs. Comfort is another area, where the electric drive vehicles have advantages. Electric motors are considered to be quieter than ICEs. Inherently, FCVs and EVs also have the capability of easily providing more electrical power to both on- and off-board electrical accessories, thus increasing the ability of the vehicles to provide more than just transportation. For example, this may offset and improve upon the emissions and noise from ICE generators used in construction. Any additional uses of electricity beyond existing applications, however, will increase the vehicle's fuel consumption and consequently increase the overall life-cycle impact of the vehicle and its fuel supply system.

Safety is a very important feature for the consumer. Rigorous design, testing and approval of vehicles take place before they can meet government safety requirements and are allowed to be sold. This is generally enough to ensure consumer confidence in a vehicle; however, problems have arisen in the past with vehicles that prove to be consistently more dangerous than others (e.g., several incidents of rollovers for sport utility vehicles resulted in a negative public image). Such instances can be critical to the success of a new vehicle technology and should be of prime importance to technology developers.

Table 6.1 Comparison of Vehicle Performance Against the Gasoline ICEV

Performance Criteria	Diesel ICEV	HEV	NGV	EV	FCV
Safety	Comparable performance	Comparable performance	Comparable performance	Comparable performance	Unknown
Acceleration	Tends to be lower performance.	Greater performance	Tends to be lower	Greater performance	Greater performance
Maintenance	Better performance	More complex	Comparable performance	Better performance	Unknown
Range	Greater	Greater	Less	Much less	Less for Hydrogen, Only Slightly Less for Methanol
Noise	Poorer performance.	Improved due to a smaller IC engine and battery only mode in certain driving conditions	Comparable performance	Quieter	Quieter

6.1.2 Vehicle Refuelling

The consumer must also accept the refuelling requirements and procedures of a new vehicle technology and related supply infrastructure if the vehicle is to be successful. The LCVA scoping process has identified two aspects of vehicle refuelling as of prime importance: safety and convenience.

Safety is a primary concern for consumers and has been identified by many as a significant hurdle in the acceptance of alternative fuels such as hydrogen. The safety issues related to fuels can be defined as both real and perceived. These issues will be discussed in more depth in Section 6.2.1, safety from a community perspective. The same safety issues need to be addressed in order for both the community and the consumer to accept a new fuel into their daily life.

Convenience in refuelling is another significant issue. Consumer behaviour when refuelling vehicles is a well-established routine. Any new refuelling routines must be nearly as convenient as refuelling a gasoline or diesel vehicle, if not more so. The technical challenges related to this aspect of operation are discussed in Section 7.3.

For gaseous fuels, the consumer will be required to use different refuelling apparatus and procedures than are presently used for liquid fuels. Refuelling time is likely to be very similar for gaseous and liquid fuels, although refuelling hydrogen conveniently at 700 bar has yet to be accomplished. Refuelling location has the potential to be greatly improved for gaseous fuels. Compressed hydrogen and natural gas can be far more readily distributed than liquid fuels and could even be available at the home. Home refuelling does raise additional safety concerns, however, given the potential for improper operation and maintenance.

Liquefied gases pose a different set of fuelling requirements since liquefied hydrogen and natural gas exist at extremely low temperatures. Additional safety precautions are needed to ensure that the fuel does not come in contact with people or unprotected objects. Presently, this type of fuelling requires an automated system or a trained fuelling technician.

Electric vehicles have very different refuelling characteristics when compared with liquid or gaseous fuels. Electric vehicles take several hours to fully recharge their battery pack, requiring personalized chargers, possibly at multiple locations. This, along with the range limitations of EVs, requires major behavioural changes in the vehicle operators.

6.2 Community Expectations

For a new product or service to be successful, it requires not only consumer acceptance, but acceptance by the community or society. If a new product is opposed by a large group of people, public pressure on consumers or the government may reduce the product’s ability to sell or even result in government restrictions.

The impact of a new vehicle technology on the general public can be enormous, since vehicles and their supporting infrastructure are a large part of the daily life of the average Canadian, especially within urban areas. This impact is felt not only when people directly use and refuel vehicles, but when vehicles are used by others around them.

6.2.1 Fuel Safety

Safety is a primary concern on the public agenda, and is a consideration at all stages of fuel infrastructure development. The fuels discussed in this report have very different handling requirements, and physical properties. Though all fuel infrastructure systems will inevitably be designed to minimum standards, it is of interest to establish a comparison of the emerging alternative fuels to those we are already familiar with in the transportation market. This marketplace benchmark reference helps us understand what may require attention in a situation of emergency, and to make judgments upon new fuel supply options.

The risks associated with each fuel occur at many different types of locations. Each of these locations poses a different risk to the public. For example, vehicles, which are highly dispersed and travel in uncontrolled environments, carry a relatively small volume of fuel; whereas fuelling stations and central fuel storage facilities contain large amounts of fuel in a more controlled environment. Also, each vehicle / fuel supply system exposes the public to certain fuels through different activities and to differing degree of exposure. Relatively speaking, distributed fuel production at refuelling stations requires less fuel to be stored on-site compared to fuels that are distributed from a centralized facility on a weekly basis. Assessing the risks of each fuel is beyond the scope of this study, but a general description of fuel properties is included below. A comparison of fuel characteristics is presented in Table 6.2.

Gasoline

Gasoline is extremely flammable, is highly volatile with vapours heavier than air, and has a corresponding risk of fire and explosion. Gasoline contains known and probable human carcinogens, and presents concerns for ingestion, eye or skin contact, and inhalation. Gasoline also contains a relatively high proportion of hydrocarbons that can affect the human nervous system. Gasoline evaporates quickly and leaves little residue when spilled. It also spreads on water surfaces and quickly penetrates porous soils and groundwater (California Energy Commission web site 1999).

Table 6.2 Comparison of Fuel Characteristics[3]

	Gasoline	Diesel	Methanol	Natural Gas	Hydrogen
Toxic to skin	moderate	moderate	moderate to high	No	No
Toxic to lungs	moderate	moderate	moderate	No	No
Ingestion risk[4]	Yes	Yes	Yes	No	No
Specific gravity (air=1.00)	3.4	>4.0	1.11	0.55	0.0675[5]
Auto-ignition temp, °F (Temp req'd for spontaneous ignition)	500	500	793	1200	1050-1080[6]
Limits of flammability (% volume in air): Lower % / Upper %	1.0 / 7.6	0.5 / 4.1	5.5 / 44.0	5.3 / 15.0	4.1 / 74 (u)
Luminous flame	yes	yes	pale blue, nearly invisible	ranges from yellow to nearly invisible	pale blue, nearly invisible[7]
Storage state[4]	liquid	liquid	liquid	compressed or liquefied gas	compressed or liquefied gas

Diesel

Diesel fuel has a very high flashpoint, implying a higher safety margin than gasoline in terms of handling. By most fire-safety measures, diesel is a safer fuel than gasoline or natural gas. In addition, if spilled, diesel is not as likely to readily spread on water as gasoline. Diesel does present concerns for ingestion, skin contact and inhalation.

Methanol

Methanol is toxic in handling, and is considered as a contaminant if spilled. There are safety concerns with ingestion (potential blindness – 100 to 125 ml is considered the usually fatal dose[8]), eye or skin contact, and inhalation of methanol. Methanol is not known to be a carcinogen, reproductive or mutagenic hazard, and is not known to pose a threat to a fetus (California Energy Commission web site 1999). A recent study concluded that methanol is not persistent in the environment because it readily degrades in air, soil and water, and has no persistent degradation intermediates (Malcolm Pirnie Inc. 1999).

Low-flame luminosity makes methanol difficult to detect in the daylight. Additives may be added to create a more visibly detectable flame, but any additive may need to be removed at the fuel cell to avoid fuel cell degradation. According to the U. S. Environmental Protection Agency, M-85 (85% methanol and 15% gasoline) has a much lower frequency of vehicle-related fires and a lower hazard to people and property. Not only is M-85 more difficult to ignite than gasoline (due to its high flash point), if ignited it

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[3] Natural Fuels Company, LLC 2002 except where indicated
[4] General knowledge
[5] Defense Service Centre 2002
[6] Borusbay 1989
[7] Air Products 2002
[8] University of Dallas, Department of Chemistry, Methanol Material Safety Data Sheet

burns in a more controlled manner with less heat than other transportation fuels. In addition, methanol fires are extinguished simply and quickly by pouring water on the flame (California Energy Commission web site 1999).

Natural Gas

Natural gas is neither corrosive nor toxic, its ignition temperature is relatively high, it is lighter than air, and it has a narrow flammability range, making it an inherently safe fuel compared with other fuel sources. Natural gas cannot contaminate soil or water. It will always rise to the atmosphere when not confined, unlike other fuels which are heavier than air and can pool, either as a liquid or a vapour, upon the ground. Natural gas contains a distinctive odorant (mercaptan) that is added to the fuel and allows natural gas to be detected at 0.5% concentration in air, well below levels which can cause drowsiness due to inhalation and well below the weakest concentration which can support combustion (Alternative Fuels Data Centre 2002).

Hydrogen

Hydrogen is highly flammable, and there is an explosion risk, similar to that of gasoline. Hydrogen has very broad flammability limits, which allows it to combust when at a wide range of concentrations within the air. Hydrogen has a relatively high auto-ignition temperature, but can be ignited in the air by an electrostatic discharge (a “spark”), as can most other fuels. Hydrogen is non-toxic. Because of hydrogen's lightness, any fuel leak rapidly disperses with no pooling of vapors. Hydrogen release in an enclosed space could cause asphyxiation (California Energy Commission web site 1999).

Compressed and Liquefied Gases

Compressed gases, such as natural gas and hydrogen, have additional hazards because of their highly compressed states. A large amount of energy is stored when gases are compressed and uncontrolled, rapid release of compressed gases can pose significant risks to people within close proximity. According to Powertech Labs in British Columbia where extensive testing on compressed natural gas and hydrogen tanks has taken place, tank design and experience with failure modes indicates that these occurrences are rare.

Liquefied gases have some additional safety issues that compressed gases do not have. Skin contact with liquefied gases or the hardware that is cooled by liquefied gases can freeze tissue and inflict serious cryogenic burns. Also, gas detectors must be installed at facilities, because odorants cannot be added to liquefied gases (California Energy Commission web site 1999).

Electricity

Batteries must be handled carefully during recharging and disposal. For those batteries that use acid in liquid form, possible leaks (although most battery packs are sealed) may cause chemical burns. Care must also be taken to avoid electric shock; the battery packs store enough energy to produce dangerous or lethal shocks. Electrical circuits are self contained and grounded to limit the risk of shock from the vehicle frame (California Energy Commission web site 1999). Inductive charging, which has no direct flow of electricity from the charger to the vehicle, is also used on some electric vehicles so operators cannot be directly exposed to electric currents.

6.2.2 Infrastructure Safety

Other significant safety risks that have been identified in the upstream supply of fuel are:

- pipeline breaks and explosions
- industrial facility accidents
- spills and collisions from truck, rail and ocean going freight transport of fuels

- operational spills (including on and offshore drilling spills)
- proliferation of nuclear materials from nuclear power plants
- vandalism of or assault on industrial facilities
- electromagnetic fields from electrical devices

6.2.3 Employment

Employment is another important social factor that can have a life-altering and widely felt impact on people. It is beyond the scope of this study to compare the employment requirements for each system, but it is clear that any change from the status quo will have an impact on employment for the population. In some cases, more jobs may result; in others, fewer jobs will result. The manufacture of new types of vehicles and a new type of fuel may simply shift the tasks of people within the same industry, or there may be new industries emerging with new employment requirements. The employment requirements of a refuelling station may change; additional employees with added training may be required, depending on the requirements of a new fuel such as hydrogen.

One potential impact from large-scale change in employment concentrations between companies and/or regions is social discomfort or even crisis, such as has been experienced in many small communities when a major employer leaves town. However, considering the major players involved in developing new vehicle technologies and new fuelling infrastructures, it is obvious that many companies will not only be a part of such a transition, but will be leading it. This may result in a fairly stable employment market throughout any transition to a new transportation fuel. Even the natural resource industry, where the largest change in business may occur, is positioning itself to supply a wider range of fuels to the consumer. Admittedly, regions that rely heavily on oil production may see employment slowly redistributed to areas of other natural resource concentrations over the course of many years.

6.2.4 Aesthetics – Appearance, Noise, Odour

The appearance, noise levels and odour of a particular area are important factors determining quality of life for those who live and work in the area. This, in turn, impacts the ability of companies to obtain approvals to construct facilities or operate equipment in particular areas or at particular times. Therefore, it is in the best interests of all involved to consider the aesthetics of the facilities and equipment used to produce and distribute fuels, as well as the aesthetics of the vehicles themselves.

Every operation within the various systems has unique aspects of appearance, noise and odour that make it more or less desirable than the operations within other systems. Trying to determine which operations may be more aesthetically pleasing is a subjective exercise, based almost entirely on personal opinion and the perspective of those making the judgments. Different stakeholders will recognize different aesthetic issues and assign them different priorities. The impacts of specific operations need to be determined on a case-by-case basis and this exercise would benefit from consultation with all stakeholders. The assessment of system aesthetics that appears below is based on broad generalizations and can be used as a starting point, but must be further analyzed to identify the issues associated with specific actions. Particular attention should be given to operations located within the same vicinity as places of residence, as concerns of private citizens can weigh heavily in the process of approving new operations.

Different vehicle technologies have different aesthetic values inherent in them. Diesel engines are commonly considered to have a less pleasant odour than gasoline engines. As mentioned earlier, vehicles with electric drivetrains are quieter than ICE vehicles. Hydrogen FCVs and EVs also produce no odour, in contrast to gasoline and diesel ICE vehicles. Electric trolley buses have a large aesthetic impact on the cities they serve as they require power lines to run the entire length of the service area.

At the refuelling station, new fuels may result in new aesthetics. Since refuelling stations are widely distributed throughout populated areas, any significant change in appearance, noise or odour could have a large impact on the aesthetics of many neighbourhoods. One noticeable change may be above-ground hydrogen or natural gas tanks if these are used to add the fuels to existing stations, or if technical or regulatory hurdles require their placement above ground. This may also increase the size of refuelling station sites or limit the additional facilities of existing ones. However, underground tanks are expected in the majority of stations. Along with this on-site storage of natural gas or hydrogen, on-site compression of the fuels may impact the station's noise level, odour (although there is almost no odour if an electric compressor is used), and appearance. Another significant change for refuelling stations will occur if they begin to produce hydrogen on-site via electrolysis or small-scale natural gas reforming. The former may only impact the appearance of the station, but the latter will likely affect the odour, noise level and appearance of the station. It has yet to be determined whether site selection of small SMR units in densely populated areas will encounter major difficulties. On the other hand, if trucking of fuels to refuelling stations is completely eliminated, these stations will no longer need space to accommodate the delivery of fuel from large tanker trucks. Finally, as the amount of gasoline distributed by a station decreases, the odour from evaporating gasoline will also decrease.

Industrial facilities that are used for fuel production have a large impact on the aesthetics of their surroundings. The facilities identified in the systems studied include centralized hydrogen production, oil refineries, natural gas processing plants, power plants, and pipeline facilities. Typically, these facilities are located in industrial parks, or on the edge of populated centres so very few people live directly adjacent to them. They are, however, usually visible from roadways, and odours do have the ability to travel into residential areas; therefore, their aesthetics cannot be ignored.

Natural resource extraction and transportation are operations in which aesthetics are also important to the public. This usually occurs in rural areas. Typically, in remote areas, mines, well sites, wind farms, pipelines and electricity transmission lines are not within reach of the general public, except where they are placed close to recreational sites. However, it is common for some of these operations, such as well sites and wind turbines, to be placed on private land, where they are close to local residents. The aesthetics of these facilities has a large impact on the residents' quality of life in these areas.

6.2.5 Energy Security

The ability of a country to be self-sufficient and diversified in its energy production allows it to reduce its exposure to the uncertainty associated with energy supply from other regions or a single source. Since transportation in Canada currently relies almost solely on crude oil, diversification into other fuel sources could increase the stability of transportation availability and costs. Currently, Canada is a net exporter of almost all forms of energy, but the price of many of these natural resources is highly dependent on the American and international markets. As the United States works to improve the security of its own energy supply, decreasing dependence on oil may allow both countries to improve their transportation networks.

6.2.6 Resource Consumption

Resource consumption, as described in Section 5.5.4 is also a social issue. The distribution of society's limited natural resources is administered by the government and is intended to be performed in the best interests of society. Therefore, the general public has a vested interest in maximizing the societal benefit from the consumption of natural resources.

Each system investigated consumes a different amount of natural resources. It is the responsibility of system designers and operators, including consumers, within each distinctive region to determine the type and magnitude of resources to be allocated to vehicle operation. The results from the quantitative analysis of resource consumption for each system evaluated are shown in Figures 5.3 to 5.8. This analysis can be used as the starting point for investigating the value of resources connected to the selection of vehicles and fuel supplies in various regions of the country.

6.2.7 Land Use

In Section 5.6.6, land use as it affects the environment was described. In this section, land use is related to the impact on the ability of people to use the land for other purposes. Each of the operations listed in Section 5.6.6 uses land to produce or distribute fuel. When this land is allocated for supporting transportation systems, individuals, businesses or governments cannot use it for other activities. It causes communities to increasingly spread out in urban environments, where land is highly valued. In rural areas, the land might otherwise be used for recreation, hunting, fishing, agriculture, or small communities. In some cases the land may already be in use for one or more of these activities and will effectively displace them. Some positive land use impacts, such as flood protection through the use of reservoirs or the reclamation of land to a more useful or natural state, may also occur.

Many factors must be taken into consideration in the evaluation of the relative value of the land for its various potential purposes. This issue has the potential to strongly affect the people involved and should be investigated very carefully, particularly where loss of lifestyle will occur.

Table 6.3 Summary of Social Considerations Broken Down by System

System	A	AA	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
	Gasoline ICE	Gasoline HEV	Diesel ICE	NGV	Methanol FCV	H_2FCV - SMR Decentralized	H2 FCV - SMR Centralized	H_2FCV - Nucl ear Electrolysis	H_2FCV - Hydro. Electrolysis	H_2FCV - Coal Electrolysis	H_2FCV - NG Electrolysis	H_2FCV - Wind Electrolysis	EV - Nuclear	EV - Hydroelectricity	EV - Coal	EV - Natural Gas	EV - Wind
Vehicle Operation – see Table 6.1																	
Vehicle Refuelling																	
Dispenser type (L = liquid, G = gaseous, E = electricity)	L	L	L	G	L	G	G/L	G	G	G	G	G	E	E	E	E	E
Potential for personal refuellers				X		X		X	X	X	X	X	X	X	X	X	X
Long refuel time (LDV only)													X	X	X	X	X
Fuel Safety																	
Flammable explosive liquids	X	X	X		X												
Toxic liquids	X	X	X		X												
Flammable explosive gases				X		X	X	X	X	X	X	X					
Low flame visibility					X	X	X	X	X	X	X	X					
Compressed or liquefied gases				X		X	X	X	X	X	X	X					
Corrosive materials		X			X								X	X	X	X	X
Electric shock													X	X	X	X	X

Table 6.3 Summary of Social Considerations Broken Down by System (continued)

System	A	AA	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
	Gasoline ICE	Gasoline HEV	Diesel ICE	NGV	Methanol FCV	H_2FCV - SMR Decentralized	H2 FCV - SMR Centralized	H_2FCV - Nuclear Electrolysis	H_2FCV - Hydro. Electrolysis	H_2FCV - Coal Electrolysis	H_2FCV - NG Electrolysis	H_2FCV - Wind Electrolysis	EV - Nuclear	EV - Hydroelectricity	EV - Coal	EV - Natural Gas	EV - Wind
Infrastructure Safety																	
Pipeline breaks and explosions	X	X	X	X	X	X	X				X					X	
Industrial facility accidents	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Spills and collisions from truck, rail and ocean vessels	X	X	X		X		X	X		X			X		X		
Operational spills	X	X	X	X	X	X	X	X			X					X	
Nuclear proliferation								X					X				
Energy Security																	
Dependence on oil	X	X	X														
Resource consumption – see Section 5.5.4																	
Land use – see Table 5.18																	

Table 6.3 Summary of Social Considerations Broken Down by System (continued)

System	A	AA	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
	Gasoline ICE	Gasoline HEV	Diesel ICE	NGV	Methanol FCV	H_2FCV - SMR Decentralized	H2 FCV - SMR Centralized	H_2FCV - Nuclear Electrolysis	H_2FCV - Hydro. Electrolysis	H_2FCV - Coal Electrolysis	H_2FCV - NG Electrolysis	H_2FCV - Wind Electrolysi s	EV - Nuclear	EV - Hydroelectricity	EV - Coal	EV - Natural Gas	EV - Wind
Aesthetics																	
Vehicle aesthetics – see Table 6.2																	
Compressors and above ground storage tanks for gaseous fuels				X		X	X	X	X	X	X	X					
Refuelling station hydrogen production						X		X	X	X	X	X					
Refuelling station odour	X	X		X	X	X											
Truck transport in populated areas	X	X	X		X		X										
Industrial facilities	X	X	X	X	X	X	X	X		X	X		X		X	X	
Wind farms or hydroelectric facilities									X			X		X			X
Coal, oilsands or uranium mines	X	X	X					X		X			X		X		
Oil and gas production	X	X	X	X	X	X	X				X					X	
Electricity transmission lines				X		X	X	X	X	X	X	X	X	X	X	X	X
Pipelines	X	X	X	X	X	X	X				X					X	

7 Technical considerations

During the course of the LCVA, many technical challenges and opportunities confronting the introduction of new vehicle technologies and fuel infrastructure were identified, and these are presented here. It is assumed that existing fuels have overcome the necessary technical challenges of operating within current requirements and therefore they are not discussed in detail within this section. This list of technical considerations is by no means complete and inclusion within the list does not indicate level of importance. These considerations should, however, be kept in mind when evaluating the ability of technologies to be available in the near future. Table 7.1, at the end of Section 7, summarizes the bulk of these considerations and identifies the specific systems and vehicles for which they apply.

7.1 Safety

Each of the vehicle and infrastructure safety considerations mentioned in Sections 6.2.1 and 6.2.2 presents a technical challenge to maintain an acceptable level of risk. For emerging technologies, the challenge is to design equipment and procedures within acceptable safety standards. For the three alternative fuels considered in this study, natural gas, hydrogen and methanol, several safety challenges have previously been identified.

Facilities where gaseous or liquefied fuels are stored, whether they are refuelling stations or parking garages, may require modifications to ensure that they have adequate ventilation and leak detection devices. Many types of detectors currently exist for natural gas, but inexpensive devices for hydrogen detection are still under development. Electric vehicles with batteries that produce hydrogen during charging also require these safety considerations. Methanol ground monitoring may be required in areas of service with immediate access to water bodies or the water table. Additives can be used in both methanol and hydrogen to increase flame visibility and in hydrogen to provide a detectable odour, but these may not be used since any contaminants would need to be removed before the fuel reaches the fuel cell. Hydrogen diffusion and embrittlement of metals also need to be eliminated through the use of appropriate materials for hydrogen storage and transportation. Corrosion of materials through contact with methanol requires appropriate materials to be used as well.

7.2 Integration with Existing Infrastructure

The integration of fuel distribution systems for hydrogen, methanol and natural gas with existing infrastructure will pose many technical challenges. In many cases, completely new, independent infrastructure systems will need to be built, while in other scenarios, existing transportation and distribution infrastructure can be used.

At conventional refuelling stations, storage tanks for hydrogen or natural gas will need to be added, along with any equipment required for on-site hydrogen production. Depending on the initial capacity required at the station, this equipment might grow in size over the course of several years as alternative vehicles gain market share. New dispensers and fuel lines will need to be installed and the overall size of some stations may need to be increased, or the size of other facilities at the station decreased. Stations may be entirely redesigned if layout does not need to be governed by tanker truck space requirements. Many different configurations will need to be considered for hydrogen production and storage at the refuelling station.

Using existing gasoline and diesel infrastructure for methanol, or natural gas pipelines for hydrogen, will require adaptations due to the nature of the fuels. Methanol is more aggressive towards certain metals than diesel or gasoline and may not be compatible with some existing fuel tanks. Hydrogen molecules can react with some metals (e.g., hardened steel) to cause embrittlement (BOC Gases 1999). The hydrogen can be mixed with natural gas to reduce embrittlement of an existing natural gas pipeline, for instance, but this would require on-site separation at the fuelling station. Alternatively, new hydrogen pipelines would need to be constructed.

Of the primary energy sources considered in this report, wind power and run-of-the-river hydroelectricity are the technologies identified as being intermittent, thereby affecting the convenience of the consumer to have fuel available upon demand. For all of the primary energy sources, capacity in the form of oil and gas fields, coal, uranium or oilsands mines, wind farms or hydroelectricity stations must first be built up to suitable levels, often on a continuous basis involving large capital investments. The natural resource used as the primary energy source must also be in place in significant quantities. Wind and water resources are some of the most easily accessible natural resources, but they are also constantly changing. Thus, they are unable to provide a consistent fuel supply on their own. Several methods of overcoming the inconsistency of these natural resources are: to create a capacity to store fuel (hydroelectricity reservoirs or large hydrogen storage facilities are possible alternatives, each with benefits and disadvantages) and to diversify the fuel supply sources so that the entire system is able to compensate for changes in wind and water resources ("smart" energy systems can balance numerous resource supplies and end-user demands to provide the best use of available resources). For example, in British Columbia, additional hydroelectric generators at the Revelstoke and Mica dams and additional transmission could be added to shape intermittent resources such as wind. In order to coordinate these methods of overcoming intermittent resources, it is possible to estimate the short-term availability of wind and water resources through the study of weather patterns. Therefore, electricity from wind power or run-of-the-river hydroelectricity alone may not provide vehicle refuelling on demand, but there are many methods of overcoming this limitation through system design and operation.

Intermittent electricity sources such as wind and solar power pose some power quality challenges to managing electricity networks. Traditionally, electricity generators have supplied a relatively consistent and controllable amount of electricity to the grid. An increasing portion of fluctuating electricity sources on the grid present some integration and operational constraints on the transmission and distribution systems. These constraints create a need for more sophisticated management of operating reserve and electricity dispatch. The integration of renewable energy is not at a level today where system stability is affected; however, as the quantity of large-scale intermittent resource development continues it is questionable as to whether advances in the technologies being deployed and increased operating experiences alone will combat all of the electrical integration challenges.

7.3 Refuelling

Refuelling with gaseous fuels, liquefied gases or electricity each have different characteristics than refuelling with liquid fuels. Since the consumer is unfamiliar with refuelling vehicles with these fuels, a unique challenge for designers is to create brand new refuelling equipment that is intuitive, convenient and safe. Alternatively, vehicles may need to be refuelled by a qualified station attendant. There is also a need for standardization of fuelling connection interfaces so equipment manufacturers and consumers will not face prohibitive compatibility problems.

Gaseous fuels, such as hydrogen and natural gas, pose inherently different refuelling challenges and opportunities from those of liquid fuels. The refuelling equipment will need to be different for gaseous fuels, requiring the operator to adapt to a new procedure for filling. The connecting apparatus and the safety features of the refuelling equipment will need to be intuitive and easy to use, while a high level of safety must be maintained in the event of unforeseen actions or circumstances. Safety procedures may include the attachment of a grounding connection to prevent the build-up of static electricity between the vehicle and its surroundings. The refuelling time of gaseous fuels depends on the pressure difference between the facility storage pressure and the vehicle storage pressure. A trade-off needs to be made between refuelling time and the energy used to compress the gas. It was assumed in this study that hydrogen at a 840 bar (12,000 psig) facility pressure was required to fill a 700 bar (10,000 psig) gaseous hydrogen vehicle within minutes.

Home refuelling appliances are possible for both natural gas and hydrogen. Natural gas would obviously be the easiest home refuelling system to install, assuming that natural gas is already supplied to the residence. A home electrolysis unit is likely the simplest method of home refuelling with hydrogen, while small natural gas reformers and pipelined hydrogen are future possibilities. For both electrolysis and methane reforming technologies, costs need to be brought down while efficiency is maintained, and convenient operating and maintenance procedures are developed.

Liquefied gases require dispensers that will not allow any fuel to be leaked given their extremely cold temperature. This may require automated refuelling systems or refuelling by a qualified attendant. It will be a challenge to keep costs low while meeting all of the safety requirements.

The refuelling of hydrogen vehicles faces not only technical challenges but also regulatory ones. Safety standards for hydrogen refuelling have not yet been developed, but several standards associations around the world are attempting to address this issue. When completed, these guidelines will provide valuable direction for companies attempting to design the next generation of fuelling stations.

Refuelling battery electric vehicles are not likely to present a challenge to the majority of users in terms of operating procedures, but the speed of refuelling will require major behavioural changes. The GM EV1 takes an estimated six to eight hours for a full recharge. Attempts to overcome this limitation have been made by recharging electric vehicles while they are parked. This requires personalized chargers to be placed at the major stopping points of EV owners, a task that requires many charging units but is made easier by the fact that electricity grids to distribute the fuel are already in place.

7.4 Fuel Quality

Fuel quality can vary widely in today’s conventional fuels, but this situation may need to be eliminated, as fuel cells are very sensitive to fuel quality.

Currently, gasoline and diesel fuel from different feedstocks and refineries have different levels of sulphur and other contaminants, as well as different octane ratings, which will have an effect on an engine’s performance and emissions. Starting in 2004, the sulphur content of gasoline will be limited to 30 ppm, a drop of over 90% from the 1998 national average of 360 ppm. It is also expected that diesel-fuel sulphur levels will be reduced to 15 ppm from the current limits of 500 ppm. Emissions of SO_X and other vehicle pollutants are expected to decrease owing to the fact that SO_X emissions tend to reduce the effectiveness of new catalytic converters (which reduce tailpipe pollutant emissions).

Fuel cells, on the other hand, require nearly zero contaminants (99.99% pure) to function efficiently and to maintain a reasonable lifespan. Electrolysis is inherently one of the cleanest forms of hydrogen production, able to generate 99.99% pure hydrogen (Fairlie 2000). Steam methane reforming of natural gas, on the other hand, produces fuel with a purity of 99.95% (Spath 2001). Additional equipment, such as a Pressure Swing Absorption (PSA) unit, will be required to improve fuel quality from reformers so that adequate efficiency of a fuel cell vehicle can be maintained.

7.5 Fuel Storage

It was previously mentioned that range is a critical limitation of the electric, hydrogen fuel cell, and natural gas vehicles – a problem that requires advancements in fuel storage capabilities.

Battery technology has seen considerable advancements in the last ten years with the commercialization of nickel metal hydride (NiMH) and lithium ion (Li-Ion) batteries, whose higher energy densities provide increased range over more traditional lead-acid batteries. Unfortunately, the range of NiMH-powered vehicles, such as the GM EV1, is still well below the range of gasoline vehicles. It is unknown how far battery developers are expecting to advance battery technology in the near future, but they need to increase energy density by as much as six times before electric vehicles become comparable to conventional vehicles in terms of fuel storage.

Hydrogen and natural gas, in gaseous forms, require very different storage and transfer equipment from conventional liquid fuels. It was estimated that hydrogen would need to be stored at 700 bar (10,000 psig) in order to reach the 600-km range desired by the consumer. This would require the development of storage tanks that store up to 840 bar (12,000 psig) at the refuelling station, for fast-filling capabilities, and up to 700 bar on-board the vehicle without compromising the interior passenger or cargo space beyond acceptable limits. Fortunately, at the fuelling station space is not nearly so critical as it is within the vehicle, thus giving designers more flexibility. Currently, hydrogen is stored at 350 bar (5000 psig) in carbon fibre-wound tanks with an aluminum liner.

In order to reach the targeted on-board storage pressure requirements for hydrogen vehicles, new compressor technology would also need to be developed. Fittings, control valves and dispensers also need to be developed to handle these pressures.

A number of other hydrogen storage technologies are currently under development, which may allow FCVs to achieve ranges comparable to gasoline ICEVs. Metal hydrides can be used to absorb hydrogen and store it at high energy densities, although the mass of metal hydrides required for a single vehicle may be prohibitive. Sodium borohydride is among many chemical compounds that can store hydrogen in a reversible process, which requires handling and recycling of the end by-product.

Natural gas fuel storage systems have been operating for many years, and the technology is in place to assure the fuel distribution infrastructure is as safe as any other. Natural gas refuelling facilities typically draw natural gas from a local pipeline and compress it on site to 250 bar (3600 psig). The natural gas is then stored on-board vehicles at 225 bar (3200 psig).

The technical challenge of overcoming range limitation is an important one for alternative fuelled vehicles that wish to provide performance equivalent to that of conventional vehicles. However, it is not an absolute requirement for all consumers. Owners and operators of electric and natural gas vehicles have effectively altered their driving and refuelling habits to accommodate for the vehicle’s shorter range, and to utilize the opportunities for more convenient refuelling at personalized sites and fleet locations. For example, there are not the same attempts to increase NGV range through higher storage pressures as there is for gaseous hydrogen FCVs. This may be a result of the high proportion of NGVs being operated within urban vehicle fleets where there are not the same range requirements as for personal vehicles. Gaseous hydrogen FCVs can be used similarly in niche applications, effectively eliminating the need for increasing hydrogen storage capabilities. However, this results in a limited market that does not allow for economies of scale to reduce the costs of FCVs as quickly.

7.6 On-Site Hydrogen Production

The production of hydrogen at refuelling stations via steam methane reforming and electrolysis requires a balance between storage capacity and the ability for the production equipment to meet short-term fuel demand, as this changes on an hourly, daily and monthly basis. The ability of the hydrogen production and compression equipment to meet short-term demand depends on the overall capacity of the units and their ability to respond to demand. It is therefore necessary for this equipment to be over-sized to meet the peak demand that will be placed on them. This peak demand can be adjusted depending on the storage available at the refuelling station, but this also increases the overall station costs.

It is certain, however, that on-site SMR and electrolysis units will need to operate intermittently and at part-load, as well as at full-load. Electrolysis units are able to do this relatively easily and therefore are ideally suited to such an application. Steam methane reforming units, on the other hand, require high temperature reactions to take place, making them more difficult to operate on a fluctuating load. Cycling of the SMR units from ambient temperatures to high operating temperatures is likely to stress the materials within the units and may cause relatively short product lives. It also may be difficult to operate the SMR units at levels as low as 30% of their full capacity. These design and operational considerations must be taken into account when designing both the hydrogen production equipment and the entire refuelling station.

7.7 Lifetime

The useful lifetime of a vehicle is very important for determining its relative cost and environmental performance. Vehicle lifetime essentially determines the amount of value that is derived through both a financial and a physical investment in its construction. Some components of some alternative vehicles have an inherently shorter life than traditional vehicle components. This is an important factor for potential owners to consider.

The batteries used in electric and hybrid electric vehicles are limited by the number of charge/discharge cycles they go through. The battery pack for the Toyota Prius is warranted to last 8 years or 160,000 km. At some point, the battery packs would need to be replaced, at a cost of approximately $5000. An estimate for the lifetime of the GM EV1 battery pack was not available.

The PEM fuel cell in its automotive form is a relatively new technology. It is unclear how long it may last, or even if it will have a finite lifetime given the right conditions. It is known, however, that fuel cells become less efficient if pollutants enter the cell, effectively reducing the power available from the fuel cell stack. For the consumer, this may result in a continually degrading performance of their vehicle and also possibly a shorter engine lifetime than expected, if their fuel supply system allows a high level of contaminants to reach the cells. Fuel quality assurances and effective on-board pollutant clean-up devices can be used to protect the lifetime of the cell, thus reducing the chances of premature fuel cell retirement.

Another vehicle component that may have a limited lifetime is the pressurized cylinder used for storing gaseous hydrogen and natural gas. Due to safety codes and standards, pressurized cylinders have a limited lifetime before they need to be either retested, to ensure adequate safety margins, or replaced. Sensors for monitoring the condition of tanks are under development to potentially eliminate the need for cylinder re-certification.

7.8 Start-Up Time

The NECAR 5, with on-board methanol processing, currently requires a period of time for start-up before it can be driven. This is due to a number of system features, including the requirement to warm up the on-board reformer. Maintaining a “warm” reformer may shorten the start-up cycle, but this will also increase overall fuel consumption.

7.9 Fuel Flexibility

Several technologies have the advantage of using multiple fuels as a feedstock. IC engines are a prime example; however, specific engines need to be customized to specific fuel types. There are some ICEVs that are capable of switching from one fuel to another (e.g., gasoline and natural gas), or using different blends of fuels (e.g., biodiesel with diesel or ethanol with gasoline).

A partial oxidation (POX) reformer can convert a wide range of fuels, including gasoline, naptha or ethanol. This may allow either FCVs or ICEVs to operate on hydrogen while having considerable flexibility regarding on-board fuel storage and fuel source.

On a system wide basis, each of the vehicle technologies investigated is capable of using multiple feedstock types.

7.10 Other Technologies

For the systems analyzed, there was often more than one type of technology that could be considered for each unit process. In these cases, the most advanced or common technologies were typically chosen, and in a few cases, a sensitivity analysis was performed to investigate the impact of choosing a particular technology over another. Some of the other (emerging) technologies that were considered are briefly described here.

7.10.1 Hydrogen Production Using Reformers

Hydrogen production using hydrocarbon reformers are of three basic types: steam methane reformers (SMR), partial oxidation reformers (POX) and autothermal reformers (ATR). SMR technology is well developed and is widely considered the least expensive method of obtaining hydrogen. SMR has a long history in the industrial sector, primarily for the production of chemical and pharmaceutical products, and is widely used in petroleum refineries. Steam methane reforming is endothermic: part of the fuel is consumed to provide the necessary heat input. The output of the SMR is 70% hydrogen and requires purification to become usable within fuel cells. Partial Oxidation reactors are simpler devices than SMRs and are suitable for making hydrogen from a wider range of fuels. The exothermic nature of the reaction within the POX reactor allows for the reaction to be more responsive than SMR to variable loads, an important feature for on-board processing. The hydrogen output concentration is typically 30%, significantly lower than SMR due to the large amount of oxygen (and nitrogen if air is used as the source of oxygen) required within the reactor, and hence requires significant purification. Autothermal reforming is the least developed; it combines the SMR and POX processes so that the heat production of the POX offsets the heat requirements of the SMR. Autothermal reforming produces hydrogen of a higher purity than POX but a lower purity than SMR. Autothermal reforming can possibly offer the unique benefits of both SMR and POX.

7.10.2 Vehicles

Many ideas for increasing the efficiency of conventional and alternative vehicles have been investigated and many still remain as potential opportunities. Concepts that have been developed for the U.S. Department of Energy’s Partnership for the Next Generation of Vehicle (PNGV) and FreedomCAR programs, and used in the Rocky Mountain Institute’s “Hypercar” include the use of light-weight materials and hybrid electric drivetrains. These concepts can be used with any of the vehicle types investigated, but it should be noted that the benefits of using on-board battery storage are less when using a fuel cell engine rather than an IC engine, because the fuel cell engine does not consume fuel while the vehicle is stopped.

Over the past decade per-vehicle emissions from gasoline- and diesel-powered vehicles have been reduced dramatically. There is every reason to believe this trend will continue for the gasoline and diesel market, as well as for the vehicle market in general, with the onset of the hybrid and fuel cell–powered vehicles. Other emerging engine technologies include compression ignition natural gas engines and direct injection gasoline engines.

During investigation of the data availability for the fuel cell vehicles in this study, it was reported that the FCV systems in the prototype demonstration vehicles have not yet been fully optimized. Vehicle fuel consumption is expected to improve for future prototypes and production models.

7.10.3 Other Areas

The remaining specific technology advancements were identified by the project team and have the potential to change the performance of the systems analyzed:

- liquefaction of hydrogen using magnetic systems that use significantly fewer energy inputs
- safe conductive EV charging (inherently more efficient than inductive charging, which is currently used with the GM EV1)
- Kvaerner Plasma Arc process for reforming natural gas to hydrogen
- integrated gasification combined-cycle (IGCC) coal power plant (it will likely be more than 10 years before this is common practice)
- natural gas turbines cogenerating heat for space heating or industrial processes, thus increasing the overall plant efficiency
- in-situ recovery of crude oil from oilsands, along with other new production technologies being developed by oilsands companies, is expected to increase the efficiency of oilsands operations

Opportunities exist within each unit process to improve the efficiency and performance of both the equipment and the operations. It is generally considered that incremental efficiency improvements become smaller as technologies mature. Therefore, it is likely that emerging technologies will become increasingly more favourable compared with conventional technologies. However, it should be kept in mind that conventional technologies are also capable of germinating new technologies with a much higher efficiency potential. As was seen in the results of the environmental assessment, improvements in fuel efficiency in both the vehicles and the fuel production facilities will probably provide the greatest environmental benefit.

Table 7.1 Summary of Technical Considerations Broken Down by System

System	A	AA	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
	Gasoline ICE	Gasoline HEV	Diesel ICE	NGV	Methanol FCV	H_2FCV - SMR Decentralized	H2 FCV - SMR Centralized	H_2FCV - Nuclear Electrolysis	H_2FCV - Hydro. Electrolysis	H_2FCV - Coal Electrolysis	H_2FCV - NG Electrolysis	H_2FCV - Wind Electrolysis	EV - Nuclear	EV - Hydroelectricity	EV - Coal	EV - Natural Gas	EV - Wind
Safety																	
Gas detection and venting				X		X	X	X	X	X	X	X	LDV	LDV	LDV	LDV	LDV
Ground monitoring for methanol					X												
Compressed or liquefied gas storage and dispensers				X		X	X	X	X	X	X	X					
Methanol storage and dispensers					X												
Flame detection					X	X	X	X	X	X	X	X					
Integration with existing infrastructure																	
Materials to prevent methanol corrosion					X												
Materials to prevent hydrogen embrittlement and diffusion						X	X	X	X	X	X	X					
Integration with Existing Infrastructure																	
Additional space and equipment required at refuelling stations				X	X	X	X	X	X	X	X	X	LDV	LDV	LDV	LDV	LDV
Fibreglass liners for existing tanks					X												
Procedures to prevent hydrogen embrittlement						X	X	X	X	X	X	X					
Intermittent energy sources									X			X		X			X

Table 7.1 Summary of Technical Considerations Broken Down by System (continued)

System	A	AA	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
	Gasoline ICE	Gasoline HEV	Diesel ICE	NGV	Methanol FCV	H2FCV - SMR Decentralized	H2 FCV - SMR Centralized	H2FCV - Nuclear Electrolysis	H2FCV - Hydro. Electrolysis	H2FCV - Coal Electrolysis	H2FCV - NG Electrolysis	H2FCV - Wind Electrolysis	EV - Nuclear	EV - Hydroelectricity	EV - Coal	EV - Natural Gas	EV - Wind
Refuelling																	
Dispensers and procedures for compressed or liquefied gases				X		X	X	X	X	X	X	X					
Personal dispensers				X		X	X	X	X	X	X	X	LDV	LDV	LDV	LDV	LDV
Behavioural change													LDV	LDV	LDV	LDV	LDV
Fuel Quality																	
Legislated decreases in sulphur content of gasoline and diesel	X	X	X														
Time of year, regional and source variations	X	X	X														
Electrolysis – 99.99% pure								X	X	X	X	X					
SMR – 99.95% pure						X	X										
Fuel Storage																	
Battery energy density													LDV	LDV	LDV	LDV	LDV
Storage tanks and compressors with higher pressure capabilities				X		X	X	X	X	X	X	X					
On-site Hydrogen Production																	
Refuelling station design						X		X	X	X	X	X					
SMR operations challenges						X											

Table 7.1 Summary of Technical Considerations Broken Down by System (continued)

System	A	AA	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
	Gasoline ICE	Gasoline HEV	Diesel ICE	NGV	Methanol FCV	H_2FCV - SMR Decentralized	H2 FCV - SMR Centralized	H_2FCV - Nuclear Electrolysis	H_2FCV - Hydro. Electrolysis	H_2FCV - Coal Electrolysis	H_2FCV - NG Electrolysis	H_2FCV - Wind Electrolysis	EV - Nuclear	EV - Hydroelectricity	EV - Coal	EV - Natural Gas	EV - Wind
Lifetime																	
Battery lifetime		X											LDV	LDV	LDV	LDV	LDV
Fuel cell lifetime					X	X	X	X	X	X	X	X					
Compressed gas storage tank				X		X	X	X	X	X	X	X					
Startup and Response Time					X												
Other Technologies																	
Reforming: POX or ATR					X	X	X										
Need to establish small scale decentralized efficiency						X											
Vehicles	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Magnetic systems for H2 liquefaction							X										
Safe conductive EV charging													X	X	X	X	X
Kvaerner Plasma Arc process						X	X										
IGCC coal power plant										X					X		
Natural gas cogeneration plant											X					X	

8 Economic Considerations

The final feature of fuel cell vehicles and their fuel supply infrastructure to consider is the economics. The economic aspects that have been investigated within this LCVA are: the direct costs of producing, supplying and purchasing fuels and vehicles, and the indirect costs to people and the environment.

During the data collection portion of the study, some of the costs of the various unit processes were unavailable, particularly those for the emerging technologies. Therefore, it was necessary to use existing literature to estimate the costs associated with both the hydrogen- and the methanol-based systems. Many different sources of information were evaluated. Ultimately, the data sources used were the ones that best reflected the scenarios under evaluation while also providing a good representation of the bulk of the literature and transparency. The supporting data for the economic analysis can be found in Appendix D.

8.1 Fuel Costs

One of the largest costs of operating a vehicle is the cost of the fuel. The fuel cost for travelling 1000 km will depend both on the unit cost of the fuel and on the vehicle's fuel economy. Figures 8.1 and 8.2 show the results of the fuel cost analysis for light-duty vehicles and buses respectively.

The fuel costs for the gasoline, diesel and natural gas ICEVs, including the HEV, are all based on the average retail costs of the respective fuels in Vancouver, Calgary and Toronto for the year 1999, since both 2000 and 2001 are considered to be years with exceptional fuel prices. It should be noted that since the retail price for natural gas does not currently include provincial or federal taxes, a tax rate equivalent to gasoline, on an energy basis, has been added for comparison. Electricity prices for electric vehicles are based on recent residential electricity rates for LDVs (the off-peak rate is based on the actual price offered in 1999 by BC Hydro), and medium commercial electricity rates for buses. The retail price for methanol is based on a CAN$0.14 per litre (US$0.34 per gallon) wholesale price for the year 1999. The assumptions used to calculate the pump price of hydrogen are presented in Table D.1 in Appendix D. These assumptions are based on a number of publicly available information sources and, in order to be comparable with existing fuel prices, assume economic efficiencies of mass production are used. The taxes on hydrogen and methanol are assumed to be equivalent to gasoline taxes on an energy basis.

The improved fuel economy of the diesel IC LDV and the HEV, with respect to the gasoline ICE base case, shows a significant decrease in fuel costs for all three cities. On average, the fuel costs for the diesel Jetta are 33% lower and for the Prius HEV are 43% lower than for the gasoline Focus. The higher fuel economy of the natural gas Civic, when compared with the gasoline Focus, results in 27% lower fuel costs, on average. In the bus scenarios, the higher fuel consumption of the natural gas bus, when compared with the diesel bus, results in a range of fuel costs, from 25% higher than the base case in Vancouver to 51% higher in Toronto.

The methanol FCV is demonstrated to have similar fuel costs to the gasoline LDV assessed. As stated previously, the NECAR 5 data used in the study reflect a fuel consumption that has not yet been optimized fully and therefore will result in higher than expected operating fuel costs. The authors roughly estimate a potential reduction of 17% from the results presented here as the weight of the NECAR 5 continues to be optimized. Future technology advances may reduce the fuel consumption of MFCVs even further.

Figure 8.1 Fuel Costs for Light-Duty Vehicles Based on 1999 Energy Prices

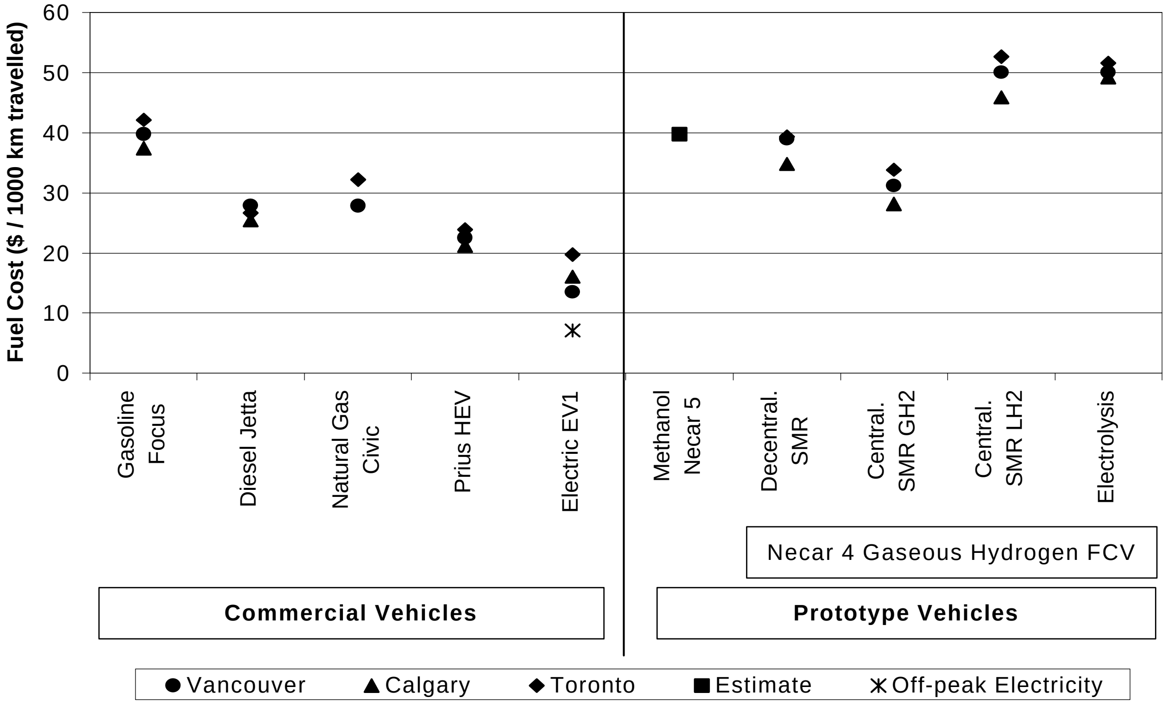
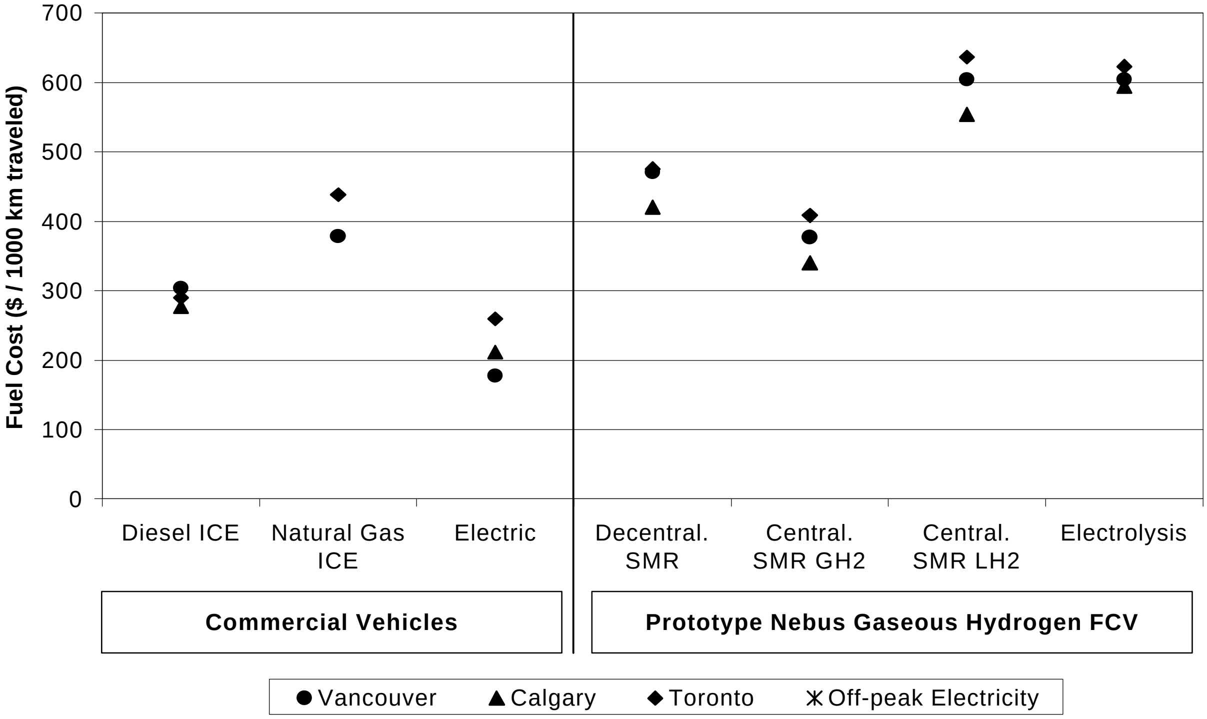


Figure 8.2 Fuel Costs for Buses Based on 1999 Energy Prices



The operating fuel cost of the hydrogen-based fuel cell vehicles is highly dependent on the method of fuel production. The NECAR 4a and the NEBUS have estimated operating fuel costs that are between 25% less and 119% more than the base case vehicles.

The cost of producing hydrogen with SMR units depends largely on the capital cost of the equipment; therefore, the economy of scale using a larger, centralized plant makes it slightly less costly than decentralized SMR units, even with the larger transportation costs of pipelining hydrogen. The costs of hydrogen for a FCV from a centralized plant are approximately 22% less than the gasoline Focus fuel costs and 29% more than the diesel bus fuel costs, on average. The FCV fuel costs using a decentralized SMR unit are 5% less than the gasoline Focus fuel costs and 57% more than the diesel bus fuel costs, on average. The lower cost of centralized SMR plants does not, however, overcome the increased cost of liquefying and trucking hydrogen. The added capital costs of a hydrogen liquefier at a centralized plant results in some of the highest overall fuel costs: 24% higher than the gasoline Focus fuel costs and 106% higher than the diesel bus fuel costs. Electrolysis of water to produce hydrogen at fuelling stations has slightly higher costs than the production of liquid hydrogen from a centralized SMR plant, primarily owing to the cost of electricity. A time-of-use rate of 4.5 cents per kWh was used. This value was calculated based on the time-of-use rates available from several utilities in Canada and assumes that electricity consumption occurs relatively uniformly throughout the hours of the day. This assumption requires that enough storage volume is available on-site to allow a significant portion of hydrogen to be generated at off-peak hours, which occur both at night and mid-day. Analysis has not been performed to determine whether this is a realistic assumption, since only limited information regarding specific operating procedures of small-scale hydrogen production is publicly available. Overall, fuel costs for the NECAR 4a are estimated to be competitive with fuel costs for the gasoline Focus, but the NEBUS fuel costs are estimated to be more than 20% higher, a factor that may be prohibitive for bus operators. However, it should be kept in mind that per-kilometre fuel prices are expected to decrease as the fuel cell vehicle technology matures.

The operating fuel costs for electric vehicles vary significantly between battery EVs and electric trolley buses. The battery EV can take advantage of off-peak electricity prices (if available to the consumer) by charging overnight, which is also the most likely time for charging to take place. Figure 8.1 shows that if off-peak electricity prices of 3.55 cents per kWh are used to calculate the operating fuel cost of the EV1, it results in the lowest fuel costs of any of the light-duty vehicles, 82% lower than the fuel costs for the gasoline Focus. The more likely charging scenario for a battery EV is to use a combination of on- and off-peak electricity, as it will need to be charging during most periods of inactivity. Therefore, a mixture of fuel costs will occur between the off-peak rate of 3.55 cents per kWh and the regular electricity price for the region in question. Due primarily to the increased efficiency of the EV1 compared with the other light-duty vehicles, this combination of electricity prices will still result in an operating fuel cost that is less than the other LDVs. The fuel costs for the EV1 based on residential electricity rates ranges from 53% to 66% less than the gasoline Focus fuel costs, depending on the province of operation. The electric trolley bus, on the other hand, does not have the ability to use off-peak electricity, and the relative efficiency gains over other bus technologies are not as large as the advantage of the EV1. As a result, the operating fuel cost of electric trolley buses ranges from 42% less than the diesel bus fuel costs in Vancouver to 10% less in Toronto.

8.2 Vehicle Costs

The cost of the vehicle is the largest single cost for the consumer to consider when selecting a vehicle. This will undoubtedly play a significant role in the consumer acceptance of a new vehicle technology. The following analysis uses both actual prices for cars, and projections on the cost of vehicle components for fuel cell vehicles when mass-produced in high volumes. Potential financial incentives for purchasing alternatively fuelled vehicles for either individual consumers or fleet operators have not been considered, but may become an important factor as the demand for ultra-low emission vehicles increases. Based on the lack of publicly available information, the cost of fuel cell buses was not estimated.

As can be seen in Tables 8.1 and 8.2, the price available in the United States for the light-duty vehicles studied are within US$5000 of their gasoline counterparts, with the exception of the EV1. This does not automatically translate to a similar situation in Canada, as the ratio of American to Canadian prices changes depending on the specific model. The more abundant gasoline and diesel cars have a more favourable Canadian price than the exchange rate would dictate, whereas the relatively low production HEV has a Canadian price that is nearly the same as the American price. It is assumed that for the other emerging NGV and EV technologies, the Canadian price is based on the American price and the current exchange rate since the natural gas Civic and the EV1 are not presently available in Canada. However, it is also expected that as the production volumes grow and the Canadian market for these new vehicle technologies increases, the Canadian price will not be based on the American price, thus resulting in more competitive Canadian prices compared with the gasoline and diesel cars.

Table 8.1 lists the manufacturer's suggested retail price for the vehicles evaluated in this study along with an equivalent gasoline ICEV, except for an ICEV equivalent to the GM EV1. The diesel ICEV has the least price difference with the equivalent gasoline ICEV (CAN$1,960). Both the HEV and the natural gas ICEV are estimated to sell for approximately 45% and 57% respectively of the price of their respective gasoline ICEV counterparts. The GM EV1 is estimated to cost over 2.5 times as much as the Ford Focus, Toyota Corolla and Honda Civic DX.

Table 8.1 Car Manufacturers' Suggested Retail Prices

Car	Canadian Price (CAN$)	American Price (US$)
Ford Focus SE (gasoline)	$21,265	$15,060
VW Jetta GL TDI (diesel)	$23,450	$18,145
VW Jetta GL (gasoline)	$21,490	$16,850
Toyota Prius (HEV)	$30,900	$20,450
Toyota Corolla LE (gasoline ICEV)	$21,365	$15,480
Honda Civic GX	$31,553*	$20,510
Honda Civic LX (gasoline)	$20,100	$15,910
GM EV1 (NiMH)	$67,684*	$43,995

*calculated using 0.65 US$/CAN$ ratio (average for 2001 – Bank of Canada)

Table 8.2 Estimated Incremental Cost Compared with Ford Focus

Vehicle	Canadian Cost (CAN$)		American Cost (US$)	
	High	Low	High	Low
H_2 FCV (NECAR 4a)	$7,429	$1,523	$4,829	$990
MFCV (NECAR 5)	$8,834	$2,657	$5,742	$1,727

See Tables D.3 and D.4 for sources of assumptions.

The estimated incremental cost of the hydrogen and methanol fuel cell vehicles was calculated based on the projected mass-produced cost of individual vehicle components along with the weight and power of the specific vehicles indicated. The results obtained were within US$3400 of other literature reviewed, indicating that there is currently a large uncertainty as to the projected costs of fuel cell vehicles. The results were also not the highest nor the lowest estimates of incremental FCV costs for the literature reviewed. In general, all of the literature estimated that fuel cell vehicles with on-board fuel processing will be more expensive than FCVs with on-board hydrogen storage. This is a result of the cost of the on-board fuel processor and the increased vehicle weight of hydrocarbon-based FCVs. Gasoline fuel cell vehicles with on-board partial oxidation reformers were predicted to be heavier and more expensive than methanol fuel cell vehicles by a range of US$260 (Ogden 1997) to US$2883 (Thomas 1998). With regard to the estimated incremental cost of fuel cell vehicles compared with other emerging technology vehicles, it can be seen that fuel cell vehicles will likely have retail prices similar to or less than these other vehicle technologies once high volumes of mass production are reached. Vehicle manufacturers are targeting fuel cell vehicles to be similarly priced to conventional ICEVs.

8.3 Externalities

From an economics perspective, an externality is an effect of a market transaction that is not reflected in the costs or revenues of the action. For example, a negative externality is not borne by the acting body. Typically, this occurs because it is difficult to quantify the impact of an externality and to ensure that the acting body takes responsibility. Thus when a product, such as a vehicle, is sold, the social and environmental costs of pollution are not included in the price of the vehicle. The cost of this negative externality is thus borne by society.

Assessment of the externalities of the systems evaluated is important in order to compare the full cost and benefit of various options. Quantifying these externalities is beyond the scope of this work; however, a range of externalities have been identified:

- personal and societal value generated through vehicle operation
- air pollutant emissions and impacts on human, environmental and infrastructure health
- greenhouse gas emissions
- employment and tax revenue benefits
- safety risks and insurance costs
- subsidies and tax incentives.

9 Conclusions

The results from this LCVA demonstrate the relative benefits, disadvantages, and areas of improvement for a wide range of Canadian vehicle and fuel supply scenarios involving currently available technologies. Each of the scenarios has been evaluated based on its environmental, social, economic and technical features. From this work, decision makers will be better equipped to make wise decisions based on specific regional characteristics in order to make an effective and efficient transition to a significant reduction in the environmental impact of the transportation sector. Since some of these technologies have not yet fully matured, the relative performance of, and consequently the conclusions being drawn about, the technologies are expected to change in the future. The performance of not-yet-commercialized technologies is expected to have the greatest potential to improve, given their relatively low level of maturity.

There are many groups with interest in vehicle and fuel systems, each of which require specific attention to enable effective system design, implementation, operation and acceptance. The interest groups identified in this study are policy makers at the municipal, provincial and federal government levels; fleet operators in government, transit authorities and the private sector; consumers within the general public; technology developers and marketers; energy producers and fuel suppliers; and investors for energy, fuel and technology companies.

There are a large number of configurations that can be used for future vehicle and fuel scenarios, each involving different environmental, social, technical and economic factors. These factors depend on multiple conditions such as region of application, primary energy source, energy conversion technologies, fuel distribution technologies and methods, vehicle technology, and end-use practices. System design dictates a number of these conditions and impacts the system's performance throughout its life cycle.

The benefits and disadvantages of selecting a diesel ICEV over a gasoline ICEV need to be evaluated on an individual basis, since there are no clear benefits of using one over the other. Diesel vehicles are more fuel-efficient than gasoline vehicle, resulting in lower upstream impacts and life-cycle GHG emissions, but they also have a greater tendency for higher tailpipe and life-cycle emissions of some criteria air contaminants. Diesel vehicles are also considered to be less aesthetically pleasing than gasoline vehicles owing to higher noise levels, more distinct odour and visible emissions, but they are more reliable and have a longer range and a longer lifetime. Diesel fuel is also less easily ignited than gasoline. Financially, diesel vehicles are about 10% more expensive than their gasoline counterparts, but have, on average, 33% lower fuel costs.

Natural gas vehicles have some of the lowest environmental impacts of any internal combustion engine vehicles and have the potential to be cost-competitive, but would face fuel infrastructure and storage challenges with wide adoption. Natural gas vehicles have, for the most part, the lowest life-cycle air emissions of the ICEVs studied. Compared to the base case scenarios, air emissions decrease in every region for the majority of stressor categories and the average energy consumption is 41% lower for LDVs, but 8% greater for buses. Compared to gasoline and diesel, natural gas has fewer air pollutants of concern and is not toxic or corrosive. When released into the environment, natural gas will not contaminate soil or water, although it is a greenhouse gas. The range of NGVs is currently half that of gasoline LDVs and 15% lower than diesel buses, creating a need for higher on-board storage pressures. Compared with the base case, the natural gas LDV has 27% lower fuel costs; the vehicle cost, however, is between 30% and 60% higher than an equivalent gasoline LDV, although increased production will likely reduce vehicle costs. The fuel costs in the bus scenarios ranged from 25% higher than the base case in Vancouver to 51% higher in Toronto.

Hybrid electric vehicles present an opportunity to reduce life-cycle impacts with relatively little change to fuel infrastructure. A 43% decrease in fuel consumption compared with a gasoline LDV provides immediate environmental, social and economic benefits (e.g., air emissions, resource consumption, fuel cost, etc.) along the entire life cycle for HEVs. HEVs also provide better acceleration, greater range and less noise than conventional gasoline LDVs. On the other hand, HEVs are currently approximately 30% to 45% more expensive than an equivalent gasoline LDV, have limited battery lifetimes, and are more technically complex than conventional gasoline vehicles.

HEV technology is a relatively simple method of improving overall system performance and is available to most vehicle types as an incremental enhancement. The environmental, social and economic benefits of using HEV technology, as described previously, can be applied to ICEVs with levels of benefits similar to those identified for the gasoline HEV studied, while FCVs are capable of slightly less performance improvement owing to their intrinsic efficiency advantages over ICEVs. Other types of HEV configurations (e.g., different sizes of battery packs, IC engines and electric motors, and different amounts of fuel and electricity) can be used to alter the performance characteristics of HEV systems.

Currently, indirect methanol fuel cell vehicle technology demonstrates a mix of advantages and disadvantages compared with conventional gasoline vehicles. The MFCV has nearly zero tailpipe emission of criteria air contaminants – thus eliminating the majority of air pollutant emissions in the regions of vehicle operation – but at the current level of technology maturity, the MFCV has limited ability to significantly reduce life-cycle air emissions in several categories. Primary energy consumption is on average 9% lower than the base case. It should be noted that through further vehicle optimization, fuel consumption is expected to decrease by as much as 17% from the value used, with a corresponding decrease in life-cycle emissions. MFCVs provide better acceleration and less noise and are expected to be more reliable than conventional gasoline LDVs. Although methanol is toxic and considered a contaminant if released to the environment, it is not known to be a carcinogen, or a reproductive or mutagenic hazard, and is not persistent in the environment. Methanol also has low flame luminosity. MFCVs are expected to have a longer start-up time than conventional vehicles and require a fuel distribution infrastructure to be developed before widespread adoption can take place. Vehicle manufacturers are targeting fuel cell vehicles to be priced similarly to ICEVs; however, existing academic literature estimates that MFCVs will be between CAN$2,700 and CAN$8,800, (13% to 45%) more expensive than an equivalent gasoline LDV. MFCVs are also estimated to currently have approximately the same fuel costs as a gasoline LDV.

FCVs fuelled with hydrogen from renewable energy show the greatest opportunity for minimizing negative environmental and social impacts of vehicle / fuel supply systems. The FCV systems powered by wind and hydroelectricity in Canada have near zero life-cycle emissions and the potential for improved vehicle performance compared to conventional vehicles. Challenges do exist regarding the availability, siting and cost of renewable energy. At this point in development, hydrogen FCVs have shorter range, faster acceleration, quieter operation and a less distinct odour than conventional vehicles. Hydrogen is non-toxic and disperses quickly in the air, unless in an enclosed space, where it could cause asphyxiation. Hydrogen does have broad flammability limits and has the potential to be ignited by an electrostatic discharge even though it has a relatively high auto-ignition temperature. Vehicle manufacturers are targeting fuel cell vehicles to be priced similarly to ICEVs; however, existing academic literature estimates that hydrogen FCVs will be between CAN$1,500 and CAN$7,400, (8% to 38%) more expensive than an equivalent gasoline LDV. The cost of hydrogen from decentralized electrolysis units using a time-of-use electricity rate at 4.5 cents per kWh for a given distance is estimated to be 27% higher than a gasoline LDV fuel costs and 109% greater than a diesel bus fuel costs, given the current level of technology maturity.

Where renewable energy is not available, steam methane reforming technology is the next most environmentally benign source of hydrogen, although distribution logistics for centralized plants and the operational issues of decentralized plants remain as hurdles. For the NECAR 4a, life-cycle GHG emissions are as much as 45% less than the gasoline LDV system, while for the NEBUS they are as much as 25% less than the diesel bus system, with the potential for greater decreases in most other air pollutants. These reductions are limited to regions of low-emission electricity generation (e.g., British Columbia). This is mostly a result of the electricity requirements for hydrogen compression, although the electricity requirements for the small-scale SMR unit also have a noticeable impact on the results. In regions where coal is the primary source of electricity (e.g., Alberta), there is a smaller decrease in emissions, and even an increase in a few stressor categories, such as GHG, PM, SO_2 and NO_X. For LDVs, fuel costs for gaseous hydrogen (using pipeline delivery) are 22% less than fuel costs for the gasoline Focus, on average, but still 29% greater than the diesel bus. Based on current estimates, the fuel cost for the decentralized SMR system is estimated to be, on average, 5% less than the gasoline LDV system, but 57% higher than the diesel bus system.

Coal-based electrolysis for FCVs is not more environmentally beneficial than conventional gasoline or diesel vehicles. For the coal-based scenarios, the majority of stressor category emissions are more than twice as high as the respective base case scenarios, with the highest being a 19-fold increase in PM emissions in the Toronto bus scenario.

Natural gas–based electrolysis for FCVs has both advantages and disadvantages when considering their life-cycle air emissions. For most of the natural gas–based LDV scenarios, air emissions increase or change very little in as many stressor categories as they decrease in, whereas in the bus scenarios, life-cycle GHG and SO2 emissions increase while the other air emissions decrease. Resource consumption is estimated to be, on average, 11% and 78% more than the base cases for fuel cell LDVs and buses respectively.

Electric vehicles, both personal LDVs and trolley buses, use electricity more efficiently than producing hydrogen from electrolysis, but face major social, technical and economic challenges. For both the LDVs and buses, 66% less electricity is required for electric vehicles to travel the same distance as fuel cell vehicles. Like electrolysis-based FCV systems, environmental performance of EV systems is highly dependent on the source of electricity. Low-emission sources such as wind, hydroelectricity and nuclear power provide nearly zero life-cycle air emissions, while natural gas–based EVs are capable of more than 40% decrease in most air stressor categories. For the most part, life-cycle air emissions from the coal-based systems remain higher than the base cases in the majority of stressor categories. Light-duty electric vehicles are the most range-limited and are roughly twice the price of the next most expensive vehicle studied. Advancements in battery technologies to increase storage density and reduce costs are a considerable challenge for battery EVs. Trolley buses require capital investment and continual maintenance on electric trolley lines, which ultimately limit the versatility of the buses and have an aesthetic impact on service areas. Battery electric vehicles have the lowest fuel costs of any of the LDVs. These prices are, on average, 82% less than gasoline LDV costs using off-peak electricity at 3.55 cents per kWh, and between 53% (Toronto) and 66% (Vancouver) less using recent residential prices. For buses, the fuel costs range between 42% less than diesel buses in Vancouver to 10% less than diesel buses in Toronto.

Nuclear power plants have both positive and negative environmental and social attributes compared to other sources of transport energy. Nuclear power–based systems have near zero life-cycle air emissions, but create radioactive waste with negative safety, security and environmental impacts, some of which last thousands of years.

The use of oilsands instead of conventional oil sources has both benefits and disadvantages. Production of crude oil from oilsands requires more energy input, thus creating higher GHG and NO_X emissions. Conversely, oilsands operations create less volatile organic compounds and sulphur emissions than conventional oil production. Also, oilsands operations in northeastern Alberta are effectively concentrating the impacts of upstream oil production into smaller areas. The concentration of these impacts is likely to magnify both the benefits and disadvantages of oil production activities.

Liquid hydrogen requires a considerable increase in electricity compared with gaseous hydrogen and affects overall life-cycle environmental performance and fuel cost. In the centralized SMR-based scenarios, producing liquid hydrogen requires 5.4 times more electricity than producing gaseous hydrogen. This increases life-cycle air emissions considerably in areas dependent on fossil fuels for electricity supply. Air emissions increase marginally in areas dependent mostly on zero-emission electricity sources. The fuel costs of liquid hydrogen from a centralized SMR plant are estimated to be 60% higher than the cost for gaseous hydrogen. This results in some of the highest fuel costs of any of the fuels assessed (24% greater than the gasoline Focus and twice as high as the diesel bus).

Overall, regional considerations are very important to system performance. Environmental, social and economic impacts in individual regions depend on the source of energy, the path of energy flow, and the point of energy use. Each of these factors helps determine both the magnitude and the location of impact. The shifting of environmental, social and economic burden from one region to another is evident in a number of the systems analyzed. For example, the electricity-based systems shift many impacts from the cities of vehicle operation to regions of electricity production.

Finally, it was concluded that full systems thinking and design is critical to ensuring that environmental, social and economic performance is optimized. In the design of components for vehicle and fuel supply systems, a life-cycle approach will enable designers to identify multiple factors, including the interests of the diverse set of groups affected, that may greatly influence the success of a new product or service.

10 Further Work and Study

Over the course of this LCVA, many needs and opportunities for further study were identified. This section summarizes several important opportunities that can provide important next steps in the advancement of vehicle and fuel supply systems.

It has been demonstrated that a life-cycle approach is needed to evaluate the overall performance of vehicle and fuel supply systems. In the same respect, system performance can be improved with a life-cycle approach. This requires a variety of viewpoints to understand the system dynamics and identify opportunities for design improvements. Therefore, life-cycle systems design improvement sessions with groups of experts should be used to advance appropriate technologies and overall system design.

Other emerging technologies should be evaluated using the LCVA framework and approach. These technologies may include vehicles, fuel production equipment, fuel storage systems, or one of the technologies not selected for evaluation, which are listed in Table 3.2. This evaluation will allow technologies to be compared on an environmental, social, economic and technical basis in order to assist future decision making processes as technologies evolve.

The environmental, social, technical and economic considerations identified and discussed qualitatively in this study should be explored in more detail before definitive conclusions are drawn. Many important considerations have been raised that will directly affect the life-cycle comparison of vehicle/fuel supply systems. Further definition and evaluation of these considerations will assist in the decision-making process.

A detailed investigation of the operating requirements and opportunities for design flexibility for hydrogen refuelling stations and their associated hydrogen production, compression and storage equipment should be undertaken. There is a deficiency in publicly available information regarding the range of operating requirements and station sizes that may be used for different hydrogen production methods.

The effects of vehicle degradation and driving conditions on life-cycle performance should be investigated. These two factors will have an important influence on how systems compare over time. It is known that vehicle technologies will perform differently under a changing operating environment. This performance difference will affect the entire life cycle since fuel consumption determines the magnitude of upstream impacts.

A full transportation system analysis should be performed. This would include aspects of community planning, a broader inclusion of transportation modes, and consideration of transportation objectives in order to consider how personal vehicle and fuel-supply systems fit in. This type of analysis would allow for a more thorough comparison of transportation alternatives available to Canadians.

The results from this work should be utilized to assist in developing appropriate strategies and pathways for moving to the most environmentally, socially and economically sound personal transportation systems. It is very important that work being done to determine the life-cycle impact of transportation systems be used in decision-making processes. Evaluating the life-cycle impacts of a system, particularly energy-based systems, is a sound way to properly evaluate its important benefits and disadvantages. However, it is often difficult to grasp the entire life cycle of a complex system at the point of decision making; therefore, studies such as this one should be used to guide life-cycle thinking and make well-informed decisions.

The results from this work should be utilized to assist in designing and implementing appropriate public policy incentives to move towards the best transportation systems. Once again, this LCVA offers an assessment of the important benefits and disadvantages of vehicle / fuel supply systems as they apply to society as a whole. It is in the best interests of society to use this information to develop appropriate incentives for both vehicles and fuels with significant environmental and social advantages over conventional technologies. By doing this, the true cost of transportation will be better reflected to the consumer and, it is hoped, the amount of external costs borne by all of society will be reduced.

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Appendix A – Project Contributors

Project Team

The project team, made up of Pembina Institute staff, performed the bulk of the data collection, analysis and reporting activities.

Marlo Raynolds – Project Manager
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Gary Woloshyniuk – Senior Researcher
Jim Manson – Senior Researcher
Adrianne Gilbride – Research Support
Carissa Wieler – Editing Support

Steering Committee

The project steering committee, made up of the project partners, oversaw each stage of the project, providing guidance and direction where necessary.

Renato Legati – Ballard Power Systems
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Stephen Forgacs – Ballard Power Systems
Ron Monk – BC Hydro
Steve Brydon – BC Hydro / Government of British Columbia
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Many individuals and companies were kind enough to contribute time and effort to providing valuable data for this study.

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External Reviewers

Several versions of this report have undergone review both internally, within the organizations of the project partners, and externally, to organizations selected by the steering committee. The feedback received through each review loop was found to be extremely valuable and was used to improve the quality of the report where possible. The external reviewers, as listed below, reviewed a draft version of the report. Inclusion on the list of reviewers does not indicate agreement or endorsement of the methodology, data or conclusions presented in this report.

Venki Raman – Air Products
Sandy Thomas – H2Gen Innovations
Don O'Connor – Methanex
Ruth Talbot – Natural Resources Canada
Alex Lambert – Stuart Energy Systems
Seth Dunn – Worldwatch Institute

Appendix B – Unit Process Descriptions

Confidential information has been excluded from the following unit process descriptions.

The comments made in "Future Prognosis" were not accounted for in modelling and are simply used to provide the reader with information regarding the potential future performance of the technology.

Name:	Operate Gasoline ICEV – LDV (Ford Focus)	**UP #:**	101
Description:	Operating a conventional compact gasoline car over a combined city and highway distance.		
Background:	Baseline with which to compare other vehicle technologies with. A new model with automatic transmission that is popular in North America, and is considered typical compared to the other LDVs in the study, is used.		
Data Sources:	Manufacturer websites and dealers (vehicle specifications), Environment Canada (GHG emissions), US EPA (fuel consumption, non-GHG air emissions)		
Assumptions:	7.15 l / 100 km (33 mpg) - EPA driving cycle (based on 55% city and 45% highway driving). -Does not include: vehicle manufacture, maintenance, disposal, or oil consumption.		
Future Prognosis:	Well established technology with consistent, incremental improvements in fuel consumption and emissions.		

Name:	Operate Diesel ICEV – LDV (VW Jetta TDI)	**UP #:**	102
Description:	Operating a conventional diesel compact car over a combined city and highway distance.		
Background:	Commercially available alternative to baseline vehicle. A new model that is one of the only diesel cars available in North America with automatic transmissions, and similar power capability and size to selected baseline vehicles is used.		
Data Sources:	Volkswagen website (vehicle specifications), Environment Canada (GHG emissions), US EPA (fuel consumption, non-GHG air emissions).		
Assumptions:	5.24 l / 100 km (45 mpg) - EPA driving cycle (based on 55% city and 45% highway driving). -Does not include: vehicle manufacture, maintenance, disposal, or oil consumption.		
Future Prognosis:	Well established technology with consistent, incremental improvements in fuel consumption and emissions.		

Name:	Operate Natural Gas ICEV – LDV (Honda Civic)	**UP #:**	105
Description:	Operating a conventional compact natural gas car over a combined city and highway distance.		
Background:	Commercially available alternative to baseline vehicle. A new model that is one of the only OEM natural gas cars available in North America with a continuously variable transmission (CVT), and similar power capability and size to selected baseline vehicles is used. Vehicle conversions currently more common, but they do not provide optimal and consistent performance.		
Data Sources:	Honda website (vehicle specifications), US Department of Energy and EPA (fuel consumption, air emissions)		
Assumptions:	3.9 kg / 100 km (39 mpgge) - EPA driving cycle (based on 55% city and 45% highway driving). -Does not include: vehicle manufacture, maintenance, disposal, or oil consumption.		
Future Prognosis:	Well established technology (emerging commercial application in LDVs) with expected improvements in fuel consumption, emissions, power, and on-board natural gas storage as technologies mature, more OEM vehicles produced and new technologies emerge (such as compression ignition natural gas engines).		

Name:	Operate Diesel ICEV – Bus	**UP #:**	106
Description:	Operating a conventional diesel urban transit bus within a typical urban environment.		
Background:	Baseline with which to compare other vehicle technologies with. An aggregate of many in-use buses.		
Data Sources:	Coast Mountain Bus Company (sample vehicle specifications), Environment Canada (GHG emissions), a number of SAE papers* studying dynamometer emissions from in-use transit buses (model years 1997 – 1999) over the Central Business District driving cycle (air emissions in grams per litre of diesel), Panik** (fuel consumption)		
Assumptions:	57 l / 100 km (4.14 mpg) – on-road bus route in Esslingen, Germany. -Does not include: vehicle manufacture, maintenance, disposal, or oil consumption.		
Future Prognosis:	Well established technology with consistent, incremental improvements in fuel consumption and emissions.		

*Clark, N., et.al. 1999. "Diesel and CNG Transit Bus Emissions Characterization by Two Chassis Dynamometer Laboratories: Results and Issues." Society of Automotive Engineers (SAE), paper no. 1999-01-1469, p.12.

*McKain, D.L., et. al. 2000. "Characterization of Emissions from Hybrid-Electric and Conventional Transit Buses." SAE, paper no. 2000-01-2011, p.5.

*Northeast Advanced Vehicle Consortium. 2000. “Hybrid-Electric Drive Heavy-Duty Vehicle Testing Project - Final Emissions Report." Boston, MA, USA, p.A1.

**Panik, F., G. Dietrich. 1998. “Fuel Cell Busses in Test-Operation” or “Brennstoffzellenbusse im Feldtest.” VDI Berichte Nr.

Name:	Operate Natural Gas ICEV – Bus	**UP #:**	107
Description:	Operating a conventional natural gas urban transit bus within a typical urban environment.		
Background:	Commercially available alternative to baseline vehicle. An aggregate of many in-use buses.		
Data Sources:	Coast Mountain Bus Company (sample vehicle specifications), Environment Canada (GHG emissions), a number of SAE papers* studying dynamometer emissions from in-use transit buses (model years 1997 – 1999) over the Central Business District driving cycle (air emissions in grams per litre of diesel), Panik* (fuel consumption).		
Assumptions:	53 kg / 100 km (3.13 mpgde)– on-road bus route in Esslingen, Germany. -Does not include: vehicle manufacture, maintenance, disposal, or oil consumption.		
Future Prognosis:	Well established technology with expected improvements in fuel consumption, emissions, power, and on-board natural gas storage as technologies mature, more OEM vehicles produced and new technologies emerge (such as compression ignition natural gas engines).		

see UP# 106

Name:	Operate HEV – LDV (Toyota Prius)	**UP #:**	108
Description:	Operating a hybrid electric compact car over a combined city and highway distance.		
Background:	Commercially available alternative to baseline vehicle. The Toyota Prius is a hybrid electric vehicle (HEV) that combines a gasoline engine and an electric motor in a high-efficiency powertrain that monitors itself continuously to ensure it is operating in the most energy efficient, least polluting mode. Gasoline is the only fuel used in the Prius; charging from an external source is not used. Regenerative braking is used to recover energy from the wheels. The Prius was selected above the Honda Insight (the only other HEV commercially available in North America in 2001) since it provides a more equivalent performance to the other light-duty vehicles in this study.		
Data Sources:	Toyota Canada (vehicle specifications), Environment Canada (GHG emissions), US EPA (fuel consumption, non-GHG air pollutants)		
Assumptions:	4.05 l / 100 km (58 mpg) - EPA driving cycle (based on 55% city and 45% highway driving). -Does not include: vehicle manufacture, maintenance, disposal, or oil consumption.		
Future Prognosis:	The Toyota Prius was released in Japan in 1997 as the first commercially available HEV. With most of the world's major automakers developing HEVs, advances in technology are certain to arise quickly. HEV developers have numerous configuration options for sizing the engine and electrical components depending on the performance desired. Even though both the Prius and Insight are of a similar configuration (with engine and electric motor aligned in parallel and no external charging), there is still no dominant configuration for the industry thus increasing the opportunity for innovation to increase overall system efficiency and decrease environmental impact.		

Name:	Operate Hydrogen FCV – LDV (Ford P2000, NECAR 4, NECAR 4a)	**UP #:**	110
Description:	Operating a prototype fuel cell car over a combined city and highway distance. P2000 and NECAR 4a store compressed H_2; NECAR 4 stores liquefied H_2.		
Background:	Three of a handful of hydrogen FC cars in the world. The NECAR 4a is used in the bulk of the analysis. The NECAR 4 and 4a are used in the liquid hydrogen sensitivity (Section 5.5.3) only.		
Data Sources:	NECAR 4 and 4a – Ballard Power Systems Inc. and DaimlerChrysler*, P2000 – SAE paper**		
Assumptions:	NECAR 4 and 4a – 1.1 kg / 100 km (59 mpgge) New European Driving Cycle. Modelling assumes equivalent fuel consumption for the NECAR 4 and 4a. P2000 - 0.94 kg / 100 km (67 mpgge) - EPA driving cycle (based on 55% city and 45% highway driving). -Does not include: vehicle manufacture, maintenance, or disposal.		
Future Prognosis:	As prototype vehicles, it is expected that overall vehicle performance will improve before commercialization takes place.		

* Friedlmeier, G., J. Friedrich, K.-E. Noreikat, F. Panik. 2000. “Test Experiences with the DaimlerChrysler Hydrogen-Fueled Fuel Cell Electric Vehicle NECAR 4.” DaimlerChrysler AG. Germany. Presented at 13th World Hydrogen Energy Conference, Beijing, China, June 2000.

**Adams, J.A., et.al. (Ford Motor Company). 2000. "The Development of Ford's P2000 Fuel Cell Vehicle." Society of Automotive Engineers, Paper no. 2000-01-1061.

Name:	Operate Hydrogen FCV – Bus (NEBUS)	**UP #:**	112
Description:	Operating a prototype fuel cell bus over an urban driving cycle. The NEBUS stores compressed hydrogen.		
Background:	One of a handful of hydrogen FC buses in the world. Ballard is currently constructing fifth generation prototype buses (P5).		
Data Sources:	Ballard Power Systems Inc. (vehicle specifications), Panik* (fuel consumption)		
Assumptions:	13.4 kg / 100km - on-road bus route in Esslingen, Germany. -Does not include: vehicle manufacture, maintenance, or disposal.		
Future Prognosis:	As a prototype vehicle, it is expected that overall vehicle performance will improve before commercialization takes place.		

*see UP #106

Name:	Operate EV – LDV (General Motors EV1 - NiMH)	**UP #:**	115
Description:	Operating an electric car with a nickel-metal-hydride battery pack over a combined city and highway distance.		
Background:	Commercially available alternative to baseline vehicle. A new model that is one of the only OEM electric cars available in North America. Regenerative braking is used to recover energy from the wheels.		
Data Sources:	GM EV1 website (fuel consumption, vehicle specifications)		
Assumptions:	20 kWh / 100 km required from the AC electricity grid - EPA driving cycle (based on 55% city and 45% highway driving). -Does not include: vehicle manufacture, maintenance or disposal.		
Future Prognosis:	Utilizing relatively new technologies, electric vehicles are expected to have performance improvements as battery, electric motor, electronic control systems and charging technologies mature.		

Name:	Operate Electric Trolley Bus	**UP #:**	117
Description:	Operating a conventional electric trolley transit bus within a typical urban environment.		
Background:	Commercially available alternative to baseline vehicle. An aggregate of many in-use buses.		
Data Sources:	Coast Mountain Bus Company (fuel consumption, sample vehicle specifications).		
Assumptions:	263 kWh / 100 km – in-use fleet data for Vancouver. -Does not include: vehicle or electric line manufacture, installation, maintenance, or disposal.		
Future Prognosis:	Well established technology with expected improvements in overall performance as electric motor and electronic control systems mature.		

Name:	Operate Methanol FCV – LDV	**UP #:**	120
Description:	Operating a prototype fuel cell car with on-board methanol processing over a combined city and highway distance.		
Background:	One of a handful of MFCVs in the world. Latest MFCV prototype constructed by DaimlerChrysler. Optimization of vehicle systems continually occurring.		
Data Sources:	Ballard Power Systems Inc.		
Assumptions:	New European Driving Cycle assumed Does not include: vehicle manufacture, maintenance or disposal		
Future Prognosis:	As a prototype vehicle, it is expected that overall vehicle performance will improve before commercialization takes place.		

Name:	Refuel Gasoline Vehicle	**UP #:**	201
Description:	Refuelling a gasoline vehicle at a typical Canadian service station.		
Background:	Submersible gasoline pumps are well-established and widely-used technology. Suction pumps were previously used, but require more electricity. Stage II vapour recovery reduces fugitive (VOC) emissions.		
Data Sources:	EPA (fugitive emissions), Sunoco (electricity requirement)		
Assumptions:	Fugitive emissions: 132 mg (vehicle refuelling with stage II vapour recovery) + 80 mg (spills) per litre gasoline refuelled. Electricity: 0.49 kWh per 1000 litres refuelled (assumes 1.5 hp motor to pump 38 litres per minute) Does not include: pump manufacture, maintenance or disposal; energy requirements for ancillary equipment at service station.		
Future Prognosis:	Incremental improvements in vapour recovery requirements and pump efficiencies may take place.		

Name:	Refuel Diesel Vehicle	**UP #:**	202
Description:	Refuelling a diesel vehicle at a typical Canadian service station.		
Background:	Submersible diesel pumps are well established and widely used technology. Suction pumps were previously used, but require more electricity.		
Data Sources:	Delucchi 1998* (fugitive emissions), Sunoco (electricity requirement)		
Assumptions:	Fugitive emissions: 0.0026 g / litre diesel refuelled. Electricity: assumed the same as UP# 201. Does not include: pump manufacture, maintenance or disposal; energy requirements for ancillary equipment at service station.		
Future Prognosis:	Incremental improvements in vapour recovery requirements and pump efficiencies may take place.		

*Delucchi, M.A. 1998. "Lifecycle Energy Use, Greenhouse-Gas Emissions, and Air Pollution from the use of Transportation Fuels and Electricity." Institute of Transportation Studies, University of California, Davis, California.

Name:	Refuel Natural Gas Vehicle	**UP #:**	203
Description:	Refuelling a natural gas vehicle at a typical service station or private facility.		
Background:	Natural gas is compressed at the refuelling station to 3000 psig for LDVs and 3600 psig for buses.		
Data Sources:	ATCO Gas (LDV refuelling), IMW Compressors Inc. (bus refuelling), Sulzer (fugitive emissions)		
Assumptions:	Electricity: LDV – 0.22 kWh per Sm^3 NG refuelled (assumes 100 hp, 250 cfm compressor at 40 psig suction); Bus – 0.23 kWh per Sm3 NG refuelled (assumes 150 hp, 301 cfm compressor at 35 psig suction plus cooling and vent fans). Does not include: compressor or tank manufacture, maintenance or disposal; energy requirements for ancillary equipment at service station.		
Future Prognosis:	Incremental decrease in system leaks and improvement in compressor efficiencies may take place.		

Name:	Refuel Hydrogen Vehicle	**UP #:**	204
Description:	Refuelling a hydrogen vehicle at a private facility.		
Background:	Fugitive losses of hydrogen occur during vehicle refuelling. Compression or liquefaction, and storage of hydrogen are included in UPs# 209 and 210.		
Data Sources:	PowerTech Labs		
Assumptions:	Fugitive losses: estimated to be 0.07% Does not include: compression, liquefaction or storage of hydrogen; dispenser manufacturing, installation, maintenance or disposal.		
Future Prognosis:	Incremental decrease in system leaks may take place.		

Name:	Refuel Methanol Vehicle	**UP #:**	205
Description:	Refuelling methanol vehicle at a theoretical service station.		
Background:	Submersible pumps are well established and widely used technology. Suction pumps were previously used, but require more electricity. Stage II vapour recovery reduces fugitive (VOC) emissions.		
Data Sources:	EPA (fugitive emissions), Sunoco (electricity requirement)		
Assumptions:	Fugitive emissions: 79 mg (vehicle refuelling with stage II vapour recovery) + 48 mg (spills) per litre methanol refuelled (assumed to be 60% of gasoline fugitive emissions – Delucchi 1998*). Electricity: assumed to be the same as gasoline refuelling Does not include: pump manufacture, maintenance or disposal; energy requirements for ancillary equipment at service station.		
Future Prognosis:	Incremental improvements in vapour recovery requirements and pump efficiencies may take place.		

*Delucchi, M.A. 1998. "Lifecycle Energy Use, Greenhouse-Gas Emissions, and Air Pollution from the use of Transportation Fuels and Electricity." Institute of Transportation Studies, University of California, Davis, California, U.S.A.

Name:	Charge Electric Vehicle	**UP #:**	206
Description:	Charging an electric car with a nickel-metal-hydride battery pack.		
Background:	A 220-volt MagneCharge™ inductive charging system is used to refuel the GM EV1. Home units are typically used, but more than 1,100 public chargers in California & Arizona. The EV1 with a lead-acid battery pack can be charged from a common 110V outlet using a special charger.		
Data Sources:	GM EV1 website		
Assumptions:	Electricity consumption is included in UP# 115. Does not include: charger manufacture, installation, maintenance or disposal.		
Future Prognosis:	Utilizing relatively new technologies, electric vehicle chargers are expected to have performance improvements as charger materials and electronic control systems mature.		

Name:	Store Gasoline at Refuelling Station	**UP #:**	207
Description:	Bulk fuel transfer and storage of gasoline at service stations typical to city of vehicle operation.		
Background:	Gasoline is gravity fed into station storage tanks. In British Columbia and Ontario, balanced submerged filling is used creating less fugitive emissions than for submerged filling, which is used in Alberta.		
Data Sources:	EPA, Shell Canada		
Assumptions:	Fugitive emissions: 120 mg (storage) + 40 mg (balanced submerged filling) or 880 mg (submerged filling) per litre of gasoline. Does not include: tank manufacture, installation, maintenance or disposal.		
Future Prognosis:	Incremental decreases in fugitive emissions for filling and storage may take place. Balanced submerged filling may become a requirement in Alberta.		

Name:	Store Diesel at Refuelling Station	**UP #:**	208
Description:	Bulk fuel transfer and storage of diesel at service stations typical to city of vehicle operation.		
Background:	Diesel is gravity fed into station storage tanks. In British Columbia and Ontario, balanced submerged filling is used creating less fugitive emissions than for submerged filling, which is used in Alberta.		
Data Sources:	Australian Greenhouse Office. 1998. “Energy - Workbook for Fugitive Fuel Emissions (Fuel Production, Transmission, Storage and Distribution).” National Greenhouse Gas Inventory Committee.		
Assumptions:	Fugitive emissions: 6 mg per litre of diesel transferred and stored. Does not include: tank manufacture, installation, maintenance or disposal.		
Future Prognosis:	Incremental decreases in fugitive emissions for filling and storage may take place. Balanced submerged filling may become a requirement in Alberta.		

Name:	Compress and Store Hydrogen at Refuelling Station	**UP #:**	209
Description:	Compressing and storing hydrogen at 850 barg (12,000 psig) at a theoretical refuelling station.		
Background:	Hydrogen is either produced at the refuelling station through electrolysis or on-site steam methane reforming, or transported to the refuelling station via tube truck from a centralized plant. Electricity requirement estimates for compression are calculated using an isothermal compression calculation and a 72% efficiency factor based on industry experience. As compressed hydrogen is stored some of it will permeate the pressure vessel.		
Data Sources:	Zittel 1996* (electricity consumption), Dynetek (permeation losses)		
Assumptions:	Electricity for compression: 0.84 kWh / kg H_2 transported via tube truck (2,650 psig to 12,000 psig); 0.46 kWh / kg H_2 produced by electrolysis (5,000 psig to 12,000 psig); 2.84 kWh / kg H_2 produced on-site by SMR (100 psig to 12,000 psig). Permeation losses: estimated 3.6% of hydrogen compressed is leaked during storage. Does not include: compressor or tank manufacturing, installation, maintenance or disposal.		
Future Prognosis:	Compressors, piping and pressure vessels capable of compressing and storing hydrogen to 12,000 psig not yet commercially available.		

*Zittel, W. 1996. "Hydrogen in the Energy Sector." Hyweb website, www.hydrogen.org/knowledge/w-i-energiew-eng.html accessed September 5, 2000.

Name:	Compress and Store Hydrogen at Centralized Facility	**UP #:**	210
Description:	Compressing and storing hydrogen at 2,650 psig at a centralized hydrogen production facility.		
Background:	Hydrogen is produced at the centralized facility, compressed and stored before it is distributed to refuelling station by tube truck. Electricity requirement estimates for compression are calculated using an isothermal compression calculation and a 72% efficiency factor based on industry experience. As compressed hydrogen is stored some of it will permeate the pressure vessel.		
Data Sources:	Zittel 1996 (electricity consumption)		
Assumptions:	Electricity for compression: 1.10 kWh / kg H_2 produced via large-scale SMR (280 psig to 2,650 psig) Permeation losses: assumed minor compared with losses at refuelling station since storage pressure (2,650 psig) is much lower than 12,000 psig storage pressure at refuelling station Does not include: compressor or tank manufacturing, installation, maintenance or disposal.		
Future Prognosis:	Incremental improvement in compressor performance may take place.		

Name:	Store Methanol at Refuelling Station	**UP #:**	211
Description:	Bulk fuel transfer and storage of methanol at a theoretical service station.		
Background:	Methanol is not currently distributed in bulk to service stations. However, gasoline practices can be used to approximate the activities associated with methanol. Gasoline is gravity fed into station storage tanks. In British Columbia and Ontario, balanced submerged filling is used creating less fugitive emissions than for submerged filling, which is used in Alberta.		
Data Sources:	EPA, Shell Canada, Delucchi 1998*		
Assumptions:	Assumes the same filling practices will be used for methanol as gasoline. Fugitive emissions: 72 mg (storage) + 24 mg (balanced submerged filling) or 528 mg (submerged filling) per litre of methanol (assumed to be 60% of gasoline fugitive emissions – Delucchi 1998*). Does not include: tank manufacture, installation, maintenance or disposal.		
Future Prognosis:	Incremental decreases in fugitive emissions for filling and storage may take place. Balanced submerged filling may become a requirement in Alberta.		

*see UP #205.

Name:	Produce Hydrogen from Electrolysis at a Refuelling Station	**UP #:**	212
Description:	Hydrogen production using electricity, water and an electrolyzer takes place in a distributed manner at a refuelling station.		
Background:	The electrolysis of water to produce hydrogen and oxygen has been used for decades and is used commonly to produce pure gases for a variety of applications.		
Data Sources:	Hydrogen Systems Inc., Stuart Energy Systems		
Assumptions:	50 kWh / kg H2 used. Considered a mid-range efficiency available from several suppliers. Selected to reflect the expected performance of a refuelling station sized unit. Does not include: equipment manufacture, installation, maintenance or disposal.		
Future Prognosis:	Electrolyser manufacturers are currently engaged in major product development to reduce size and cost, and improve efficiency and reliability.		

Name:	Reform Natural Gas Decentrally	**UP #:**	213
Description:	Hydrogen production using steam methane reforming of natural gas takes place in a distributed manner at a refuelling station.		
Background:	Small-scale SMR technology is currently under development. Many units have already been used worldwide. The small-scale SMR technology used for this system is still a prototype unit and is claimed to have lower natural gas consumption than many commercial large-scale SMR units, although it also has higher electricity consumption.		
Data Sources:	Air Products and Chemicals Inc., Praxair Canada Inc., H2Gen Innovations		
Assumptions:	Does not include: equipment manufacture, installation, maintenance or disposal.		
Future Prognosis:	Currently working on a range of technologies for different segments of the emerging energy market. Engaged in a major product development plan to reduce size and cost , and improve efficiency and reliability.		

Name:	Reform Natural Gas Centrally	**UP #:**	214
Description:	Hydrogen production using steam methane reforming of natural gas takes place at a centralized large-scale facility.		
Background:	A well developed technology that is used in a variety of industrial applications.		
Data Sources:	Spath* (air emissions), Caloric (energy consumptions)		

Assumptions:	Plant includes a hydrogenation vessel, high and low temperature shift reactor, and pressure swing adsorption (PSA). There is excess 4.8 MPa steam produced in the process which can be used in external processes, thus reducing the water, natural gas and emissions allocated per kg of hydrogen produced. Reference 1 states that the emissions avoided range between 1.5% and 10% of the life-cycle emissions for the production of H_2 from steam methane reforming. It is assumed for modelling purposes that the steam is not used. Assumes a 20% pressure loss through the PSA. Assumes plant can supply approximately 25,000 vehicles per day at 5 kg of hydrogen per fill. Natural Gas: 3.23 kg NG per kg H_2 produced. Water: 18.8 litres water per kg H_2 produced. Electricity: 0.316 kWh per kg H_2 produced. Does not include equipment manufacture, installation, maintenance or disposal.
Future Prognosis:	Incremental improvement in large-scale SMR performance may take place.

* Spath, P.L., M.K. Mann. 2001. "Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming." National Renewable Energy Laboratory. Golden, CO, USA. Febraury 2001 revision.

Name:	Transmit Electricity	**UP #:**	216, 217, 218
Description:	The average long-distance transmission of electricity in Ontario, Alberta and British Columbia.		
Background:	A well developed technology that is used throughout the world.		
Data Sources:	Ontario Hydro Services Company, ATCO Electric, BC Hydro.		
Assumptions:	Ontario: 8.9% transmission and distribution losses on the aggregate of electricity production in the province. Alberta: 8.9% transmission and distribution losses on the aggregate of electricity production in the province. British Columbia: 12% transmission and distribution losses on the aggregate of electricity production in the province. 6.7% transmission and distribution losses on new, incremental electricity production in the province. Assumes new natural gas-fired power plants will be in the Lower Fraser Valley. Does not include transmission system manufacture, installation, maintenance or disposal.		
Future Prognosis:	Incremental improvement in long-distance AC transmission and transformer performance may take place. High voltage direct current (HVDC) transmission is more efficient than AC transmission, but also more costly.		

Name:	Transport Gasoline & Diesel by Pipeline & Truck	**UP #:**	219, 220
Description:	The transportation of gasoline and diesel from the refinery to the refuelling station. This includes pipelining of product to a central depot near the final destination and then distributing it within the city via tanker truck.		
Background:	A well developed technology that is used throughout the world.		
Data Sources:	Deluchi, M. 1991*. US EPA AP-42.		
Assumptions:	Assumes 310 km from Sarnia to Toronto, 330 km and 1100 km from Fort Saskatchewan to Calgary and Vancouver respectively, 120 km for the average truck distribution distance within the city. Electricity for pipeline: 12.9 kWh per million litre-km of product. Assumes electricity produced by diesel generators. Diesel for pipeline: 3.3 litres per million litre-km of product. Diesel for trucking: 33.9 litres per million kg-km of product. Does not include pipeline or truck manufacture, installation, maintenance or disposal. Leaks and/or fugitive emissions not accounted for. Size of pipe and density of product may affect power requirements. No other GHG emissions provided besides CO2.		
Future Prognosis:	Incremental improvement in pipeline or truck performance may take place.		

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

Name:	Transport Natural Gas	**UP #:**	221
Description:	The transportation of natural gas from the fields of natural gas production to the locations of natural gas consumption.		
Background:	A well developed technology that is used throughout the world. Both the release of fugitive emissions and emissions from natural gas compression are important to consider.		
Data Sources:	TransCanada		
Assumptions:	Assumes 4080 km to Toronto, 1620 km to Vancouver, and 800 km to Calgary. Each of these distances includes a 500 km gathering distance to collect the gas at a central point (Edmonton, AB). Does not include pipeline or compressor station manufacture, installation, maintenance or disposal. Maintenance history and age of pipeline will affect emission from leaks. Other transmission companies environmental profiles may differ.		
Future Prognosis:	Incremental improvement in pipeline performance may take place. Fugitive emissions per quantity of product transmitted likely to decrease as GHG emission reductions increase in value.		

Name:	Transport Methanol	**UP #:**	222
Description:	The transportation of methanol from a production facility to a refuelling station.		
Background:	Methanol is currently transported in Canada by rail over large distances and by tanker truck over smaller distances. Pipelines may be used if methanol use becomes comparable to gasoline or diesel use, but this would require modification of existing pipelines or the construction of new pipelines.		
Data Source:	Deluchi, M. 1991*.		
Assumptions:	Assumes, from Medicine Hat, AB, 3100 km to Toronto, 1260 km to Vancouver, and 290 km to Calgary. Also assumes 120 km distribution distance from the rail yard to the refuelling stations. Does not include rail or truck manufacture, maintenance or disposal.		
Future Prognosis:	Incremental improvement in truck performance may take place.		

*See UP # 219.

Name:	Transport Hydrogen via Truck	**UP #:**	223
Description:	The transportation of both compressed and liquefied hydrogen from a centralized large-scale production facility to a refuelling station.		
Background:	Hydrogen is often transported either as a compressed gas in several long, narrow pressure vessels on-board a truck or as a liquid within a tanker truck. The cryogenic truck is more common since it is capable of transporting more hydrogen than the tube truck; however, as storage pressures increase transportation as a compressed gas may become the preferred method.		
Data Source:	Gill, L. 1998. "The Environmental Benefits and Economics of Hydrogen as a Vehicle Fuel in Canada." Canadian Energy Research Institute.		
Assumptions:	Assumes that hydrogen is transported as a compressed gas, except in the liquefied hydrogen sensitivity scenarios. Diesel: 0.87 litres per 1000 kg hydrogen (assumes 25km transport distance) Does not include truck manufacture, maintenance or disposal.		
Future Prognosis:	Higher storage pressures for hydrogen are expected. Incremental improvement in truck performance may take place.		

Name:	Liquefy Hydrogen	**UP #:**	224
Description:	The liquefaction of hydrogen at a large-scale, centralized facility where the hydrogen has been produced.		
Background:	Hydrogen is often liquefied for the purpose of increasing volumetric energy density so that it may be transported more easily.		
Data Source:	Peschka, W. 1992. "Liquid Hydrogen."		
Assumptions:	A major input to the process is compression. Assumes electric compression: 10.8 kWh / kg H_2. Typical of a large scale hydrogen liquefaction plant, corresponds to ~36% Carnot efficiency. Does not include liquefier manufacture, maintenance or disposal.		
Future Prognosis:	Estimated future performance at 9.8 kwh/kg, using the same technology base.		

Name:	Store Liquid Hydrogen at Refuelling Station & Centralized Facility	**UP #:**	225
Description:	Storing liquid hydrogen at a theoretical refuelling station for refuelling liquid hydrogen vehicles & a centralized facility where hydrogen production and liquefaction occurs.		
Background:	Hydrogen is produced at a centralized plant, liquefied using large-scale liquefiers, stored on-site, and then transported to the refuelling station via cryogenic tanker truck. As liquid hydrogen is stored some of it will boil-off as it warms.		
Data Sources:	Peschka, W. 1992. "Liquid Hydrogen."		
Assumptions:	Assumes no energy input is required to maintain a liquid state. Boil-off: estimated 0.5% of stored volume per day of liquid hydrogen is released through boil-off. Assumes 5 days of production storage at the centralized facility and 1.5 days of sales storage at the refuelling stations. Does not include: storage tank manufacturing, installation, maintenance or disposal.		
Future Prognosis:	Incremental decrease in boil-off from liquid hydrogen storage may occur. Boil-off losses can also be increased by reducing storage time.		

Name:	Produce Gasoline and Diesel	**UP #:**	301a,b & 303a,b
Description:	Gasoline and diesel is produced at two separate refineries. UP 301a and 303a are used to represent the majority of scenarios. These data sets are based on 27% synthetic crude oil input to the refinery and the remainder conventional crude oil. UP301b and 303b are used to represent the oilsands sensitivity where 100% of the crude oil is synthetically produced from oilsands operations.		
Background:	Crude oil is produced either from conventional wells or oilsands operations and pipelined to refineries. Modern refineries are all unique operations that typically produce a wide variety of products and emissions.		
Data Source:	PetroCanada Products Inc. (301a & 303a), Shell Canada Products Ltd. (301b & 303b)		
Assumptions:	The PetroCanada refinery in Edmonton, AB and the Shell refinery in Fort Saskatchewan, AB were chosen to represent the production of gasoline and diesel because they provided the best available data. The emissions and energy consumption of the refineries were allocated to their products based on their total market value. Does not include refinery construction, maintenance or decommisioning.		
Future Prognosis:	Incremental improvement in conventional refinery performance may take place.		

Name:	Produce Methanol	**UP #:**	306
Description:	The production of methanol at large, centralized plants.		
Background:	Methanol is produced near the site of natural gas production, consumption or convenient shipping locations.		
Data Source:	Methanex Corporation		
Assumptions:	Data from the best performing methanol plants around the world were used. Does not include plant construction, maintenance or decommisioning.		
Future Prognosis:	Incremental improvement in conventional methanol production may take place.		

Name:	Produce Electricity – Coal – Alberta & Ontario	**UP #:**	307 & 308
Description:	The production of electricity from an aggregate of coal-fired power plants in Alberta (UP 307) and Ontario (UP 308).		
Background:	Approximately 87% and 24% of the electricity produced in Alberta and Ontario respectively is from coal. Many of the power plants were constructed in the 1970's and 1980's.		
Data Source:	Alberta: TransAlta (all categories), Alberta Energy and Utilities Board (coal consumption, NO_X and SO_2 emissions), Full Fuel Cycle Consortium* (all categories). Ontario: Ontario Power Generation (CO_2, NO_X and SO_2 emissions), Klein** (air emissions), Rothman M., H. Bailly. 1999.*** (coal consumption), Full Fuel Cycle Consortium* (CO emissions only)		
Assumptions:	Data are from the most recent years of data availability (1999 and 2000 data for most categories). Most accurate data in each category was averaged. Does not include power plant construction, maintenance or decommisioning.		
Future Prognosis:	Incremental improvement in conventional coal power plants may take place. Integrated gasification combined cycle (IGCC) and cogeneration technologies have the potential to increase overall efficiencies.		

*Full Fuel Cycle Consortium (a group of Alberta energy companies). 1995. "Full Fuel Cycle Emissions Analysis of Existing and Future Electric Power Generation Options in Alberta, Canada." Alberta Department of Energy.

**Klein, M. 1999. "Full Fuel Cycle Emissions Estimations." 13th Symposium on Industrial Application of Gas Turbines. Environment Canada, Oil, Gas, and Energy Division, Hull, Quebec.

Rothman M., H. Bailly. 1999. "Electricity Industry Issues Table Foundation Paper." Pg 78.

Name:	Produce Electricity – Hydroelectricity – British Columbia & Ontario	**UP #:**	309a & 309b
Description:	The production of electricity from both aggregate (UP 309a) and incremental (UP 309b) hydroelectricity reservoirs in B.C. and Ontario.		
Background:	Approximately 90% and 22% of the electricity produced in British Columbia and Ontario respectively is from hydroelectriciy. The majority of hydroelectricity is generated from large-scale reservoirs (system aggregate). The incremental addition of hydroelectricity in B.C. is likely to be run-of-the-river hydroelectricity with no storage capacity and a greatly reduced impact when compared to large reservoirs.		
Data Source:	B.C.: BC Hydro Ontario: Ontario Power Generation		
Assumptions:	Assumes hydroelectricity in B.C. is GHG emission free. Ontario: 6.8 kg CO_2eq / MWh electricity produced (based on year 2000 data). Does not include power plant construction, maintenance or decommisioning.		
Future Prognosis:	Incremental improvement in turbine efficiency may take place. Increased use of low-impact hydroelectricity will improve overall performance.		

Name:	Produce Electricity – Natural Gas	**UP #:**	311
Description:	The production of electricity from an aggregate of natural gas-fired combined cycle gas turbine (CCGT) power plants.		
Background:	Currently, the natural gas electricity generation technology with the highest electricity generation efficiency is the CCGT. This is the most likely to be used in new natural gas power plants in Canada. Selective catalytic reduction (SCR) is often used to reduce NO_X emissions.		
Data Source:	Marvin Shaffer & Associates. 2001.* Klein, M. 1999.** Full Fuel Cycle Consortium. 1995.**		
Assumptions:	Assumes SCR is used in British Columbia and Ontario. Most representative data was selected for use. Natural Gas: 181 Sm3 / MWh electricity produced. Does not include power plant construction, maintenance or decommissioning.		
Future Prognosis:	Incremental improvement in conventional natural gas power plants may take place. Cogeneration technologies have the potential to increase overall efficiencies.		

* Marvin Shaffer & Associates. 2001. “Multiple Account Benefit-Cost Evaluation of the Burrard Thermal Generating Plant.” Ministry of Finance and Corporate Relations.

**see UP# 307

Name:	Produce Electricity – Nuclear	**UP #:**	314
Description:	The production of electricity from all nuclear power plants in Ontario.		
Background:	CANDU reactor technology is used in Ontario to supply approximately X% of the province's electricity. The thermal efficiency of CANDU plants is approximately 28%*.		
Data Source:	Uranium consumption: Rothman, M. 1999.**, Ontario Power Generation. 2000. Air emissions: Ontario Power Generation. 1999.****, Ontario Power Generation. 2000.		
Assumptions:	Uranium consumption: 0.017 kg / MWh (average of 1996 and 2000 performance data). Air emissions: average of 1999 and 2000 plant operating emissions for OPG nuclear facilities. Includes all maintenance and operations activities.		
Future Prognosis:	No new nuclear developments currently underway in Canada.		

* D.K. Blamire. February, 1999. Nova Scotia Power Inc. report prepared for Electricity Issue Table, NCCP, "A Utility Perspective on Technology Related to Greenhouse Gas Abatement."

** Mitchell Rothman, Hagler Bailly. 1999. Electricity Industry Issues Table Foundation Paper. Pg 78.

*** Ontario Power Generation. 2000. Towards Sustainable Development Progress Report. Ontario Power Generation. Pg. 58-59.

**** Ontario Power Generation. 1999. Towards Sustainable Development Progress Report. Ontario Power Generation. Pg. 49-50.

Name:	Produce Electricity – Wind	**UP #:**	315
Description:	The production of electricity from wind turbines in Alberta.		
Background:	There is currently 38 MW of installed wind generating capacity in Alberta and 142 MW across Canada*. The actual amount of electricity generated by a wind turbine is well below the installed capacity. A capacity factor is used to rate the expected output of a power generator compared to the maximum theoretical output or installed capacity. The estimated potential wind capacity in Alberta is 1711 MW (with a capacity factor of 30% or more) and 18,651 MW (with a capacity factor of 15% or more)**.		
Assumptions:	The operation of a wind turbine is essentially emission free.		
Future Prognosis:	Wind turbines are likely to continually increase in efficiency and decrease in cost as production methods improve.		

* Canadian Wind Energy Association website [www.canwea.ca/production.htm] - July 5, 2001
** Natural Resources Canada, 1997. “Economic Characteristics of Large Scale Wind Energy Development in Alberta.”

Name:	Supply Pure Water for Electrolysis	**UP #:**	317
Description:	The supply of water from city facilities to refuelling stations where it is used to produce hydrogen through electrolysis.		
Background:	Water is routinely treated and distributed throughout cities in Canada using public facilities. The quality of water available can be directly used in electrolyzers. Water is also required in many other unit processes as a secondary input.		
Data Source:	City of Toronto, City of Calgary, Greater Vancouver Regional District		
Assumptions:	Electricity for water treatment and supply: 0.34 kWh / m3 water in Toronto, 0.35 kWh / m3 water in Calgary, 0.024 kWh / m3 water in Vancouver. In Toronto and Vancouver, assumes equivalent amounts of electricity used in water supply and sewage treatment. Natural gas for water treatment: 0.018 m3 / m3 water in Calgary, data not available for Toronto and Vancouver. Does not include water treatment facility or distribution infrastructure construction, maintenance or decommisioning.		
Future Prognosis:	Incremental improvements in equipment efficiency and treatment levels may result in little change in energy consumption.		

Name:	Mine Coal – Alberta & Ontario	**UP #:**	318 & 320
Description:	The production of coal for use in Alberta and Ontario power plants.		
Background:	The production of coal in Alberta typically takes place at surface mines near the power plant site. Ontario Power Generation states that a typical breakdown of coal supplies for Ontario power plants is 40% from West Virginia, 10% from Kentucky, 10% from Pennsylvania, 30% from Wyoming, and 10% from Saskatchewan. Coal from the US Appalachian region is typically 2.5% sulphur and mined underground whereas coal from western North America is typically 0.3% sulphur and strip mined at surface*.		
Data Source:	Air emissions for Alberta: Fording Coal, TransAlta, Full Fuel Cycle Consortium**, Klein** Air emissions for Ontario: Klein**		
Assumptions:			
Future Prognosis:	Incremental improvement in mining equipment and practices may reduce energy consumption. Increased use of coal bed methane may reduce GHG emissions.		

* Klein, Manfred, "Full Fuel Cycle Emissions Estimations," 13th Symposium on Industrial Application of Gas Turbines, Environment Canada, Oil, Gas, and Energy Division, Hull, Quebec, Oct 13-15, 1999.

** See UP 307

Name:	Mine, Process and Transport Uranium	**UP #:**	322
Description:	The production of coal for use in Alberta and Ontario power plants.		
Background:	The majority of uranium mined in Canada comes from northern Saskatchewan.		
Data Source:	Energy consumption: Andseta* Emission factors: US EPA**, NREL***		
Assumptions:	The data are representative of uranium mining operations in Saskatchewan. Includes mining, chemical processing, transport from mine, processing to UO_3 and UO_2, and fuel fabrication. CANDU (heavy water) reactors use UO_2 as a fuel whereas light water reactors require UO_3 to be enriched to UF_6. Heavy water is assumed to be recycled at a high percentage, therefore the incremental energy requirements will be small.		
Future Prognosis:	Incremental improvement in mining and processing equipment and practices may reduce energy consumption.		

*Andseta, S., M.J. Thompson, J.P. Jarell, D.R. Pendergast, "CANDU Reactors and Greenhouse Gas Emissions,"11th Pacific Basin Nuclear Conference, Banff, Canada, May 3-7, 1998

** US EPA, AP-42, Fifth Edition, Volume I, Section 1.5: Liquified Petroleum Gas Combustion, Supplement B , October 1996 and Section 1.4: Natural Gas Combustion, Supplement D , July 1998.

*** National Renewable Energy Laboratory (NREL) report "Fuel Cycle Evaluations of Biomass-Ethanal And Reformulated Gasoline, Volume II, Appendix G, K.S. Tyson, 1993.

Name:	Produce and process raw natural gas	**UP #:**	324
Description:	The production of natural gas in Western Canada.		
Background:	Natural gas is produced from wells and processed in the field.		
Data Source:	Monenco Agra, Environment Canada*		
Assumptions:	Data assumes 80% of raw gas becomes processed to sales gas, with the remaining 20% as flared gas, acid gas and by-products (ethane, propane, etc.). Data for gas processing assumes an 84% recovery rate. No mention of emissions from upstream electricty generation provided (assume not considered). No distinction between sour gas processing and sweet gas processing. No sulphur content given. Efficiency of recovery rates may vary, as well as fugitive emissions from pipelines, wells, and field dehydrators.		
Future Prognosis:	Incremental improvement in production and processing equipment and practices may reduce energy consumption.		

* Environment Canada Criteria Air Contaminants Inventory
http://www.ec.gc.ca/pdb/ape/cape_home_e.cfm - data from 1995

Name:	Produce crude oil	**UP #:**	325
Description:	The production of crude oil from conventional wells and oilsands in the Western Canadian Sedimentary Basin.		
Background:	Crude oil is produced from wells and processed in the field.		
Data Source:	Environment Canada*, Statistics Canada** Oilsands Sensitivity: Suncor***		
Assumptions:	Emissions from “Upstream Oil and Gas Industry” allocated by market value.		
Future Prognosis:	Incremental improvement in production equipment and practices may reduce energy consumption. Shift away from light oil to heavy oil and oilsands in Canada.		

* see UP 324
** Energy Statistics Handbook, Statistics Canada 2001
*** Suncor 1999 Progress Report on Env, Health and Safety, and Social Responsibility (1998 data)

Name:	Transport Crude Oil	**UP #:**	326
Description:	The transportation of crude oil from the oil fields or oilsands upgrading plants to the refinery.		
Background:	A well developed technology that is used throughout the world. This involves multiple collection systems and larger, long-distance pipelines.		
Data Sources:	Deluchi, M. 1991*		
Assumptions:	Assumes 4080 km and 3900 km and from conventional wells and oilsands operations to Sarnia respectively, 500 km and 430 km from conventional wells and oilsands operations to Fort Saskatchewan respectively (includes gathering distance for conventional wells) Electricity for pipeline: 12.9 kWh per million litre-km of product. Assumes electricity produced by diesel generators. Diesel for pipeline: 3.3 litres per million litre-km of product. Does not include pipeline or truck manufacture, installation, maintenance or disposal. Leaks and/or fugitive emissions not accounted for. Size of pipe and density of product may affect power requirements. No other GHG emissions provided besides CO2.		
Future Prognosis:	Incremental improvement in pipeline performance may take place.		

* see UP 219

Appendix C – Model Outputs

List of Tables

Table C.1 Modelling Results for Vancouver LDV Scenarios

Stressor Category	Units	1 Gasoline ICE	2 Diesel ICE	3 NGV	4 HEV	5 Methanol FCV	6 H2 FCV - Decentralized SMR	7 H2 FCV - Centralized SMR	8 H2 FCV - Hydroelectricity Electrolysis	9 H2 FCV - Natural G as Electrolysis	10 EV - Hydroelectricity	11 EV - Natural Gas
Air Emissions												
GHG	kg CO2eq	227	181	138	129	206	126	134	0	259	0	89
ADP	kg SO2eq	0.466	0.591	0.236	0.289	0.452	0.233	0.249	0	0.469	0	0.161
GLOP	kg	0.656	0.774	0.170	0.415	0.412	0.168	0.180	0	0.340	0	0.117
PM	kg	0.0201	0.0480	0.0130	0.0115	0.0132	0.0133	0.0133	0.0130	0.0223	0.0075	0.0107
SPMP	kg	0.976	1.027	0.321	0.595	0.657	0.316	0.338	0	0.637	0	0.219
SO2	kg	0.320	0.253	0.151	0.181	0.245	0.147	0.158	0	0.294	0	0.101
NOx	kg	0.210	0.486	0.122	0.156	0.297	0.123	0.132	0	0.244	0	0.084
CO	kg	0.245	0.111	0.074	0.174	0.081	0.007	0.007	0	0.044	0	0.015
Energy Resource Consumption												
Hydro-electricity	kWh	0.04	0.03	13.2	0.02	0.07	50.0	26.5	661	0	227	0
Natural Gas	m3	0	0	57.8	0	93.3	56.7	60.6	0	113	0	38.8
Crude Oil	l	99.4	68.1	0	56.2	0	0	0	0	0	0	0

Table C.2 Modelling Results for Calgary LDV Scenarios

Stressor Category	Units	20 Gasoline ICE	21 Diesel ICE	22 NGV	23 HEV	24 Methanol FCV	25 H_2 FCV - Decentralized SMR	26 H_2 FCV - Centralized SMR	27 H_2 FCV - Coal Electrolysis	28 H_2 FCV – Natural Gas Electrolysis	29 H_2 FCV - Wind Electrolysis	30 EV - Coal	31 EV - Natural Gas	32 EV - Wind
Air Emissions														
GHG	kg CO_2eq	227	181	147	128	203	170	156	671	256	0	231	88	0
ADP	kg SO_2eq	0.478	0.583	0.274	0.296	0.435	0.417	0.340	2.704	0.581	0	0.930	0.200	0
GLOP	kg	0.703	0.764	0.174	0.441	0.453	0.240	0.208	1.230	0.499	0	0.423	0.172	0
PM	kg	0.0192	0.0473	0.0153	0.0110	0.0132	0.0219	0.0179	0.1308	0.0226	0.0130	0.0480	0.0108	0.0075
SPMP	kg	1.044	1.016	0.360	0.634	0.697	0.522	0.438	3.088	0.801	0	1.062	0.275	0
SO_2	kg	0.341	0.252	0.186	0.193	0.244	0.282	0.229	1.858	0.301	0	0.639	0.104	0
NO_x	kg	0.197	0.476	0.126	0.149	0.275	0.194	0.159	1.216	0.401	0	0.418	0.138	0
CO	kg	0.243	0.109	0.086	0.173	0.073	0.053	0.032	0.628	0.045	0	0.216	0.016	0
Energy Resource Consumption														
Hydro-electricity	kWh	0	0	0.52	0	0	1.99	1.06	0	0	0	0	0	0
Wind Power	kWh	0	0	0	0	0	0	0	0	0	640	0	0	220
Coal	kg	0	0	0.01	0	0	0.03	0.01	0.37	0.00	0.00	0.13	0	0
Natural Gas	m3	0	0	57.8	0	93.3	56.6	60.5	0	115.5	0	0	39.7	0
Crude Oil	l	99.4	68.1	0	56.2	0	0	0	0	0	0	0	0	0

Table C.3 Modelling Results for Toronto LDV Scenarios

Stressor Category	Units	43 Gasoline ICE	44 Diesel ICE	45 NGV	46 HEV	47 Methanol FCV	Decentralized SMR	Centralized SMR	Nuclear Electrolysis	Hydroelectricity Electrolysis	Coal Electrolysis	Natural Gas Electrolysis	54 EV - Nuclear	55 EV - Hydroelectricity	56 EV - Coal	57 EV – Natural Gas
Air Emissions																
GHG	kg CO2eq	230	183	151	130	211	148	151	2	4	586	272	1	1	201	93
ADP	kg SO2eq	0.561	0.628	0.281	0.343	0.483	0.323	0.313	0.008	0	2.943	0.517	0.003	0	1.012	0.178
GLOP	kg	0.729	0.823	0.218	0.455	0.466	0.234	0.238	0.002	0	1.124	0.416	0.001	0	0.387	0.143
PM	kg	0.0252	0.0514	0.0150	0.0144	0.0132	0.0209	0.0174	0.0130	0.0130	0.3884	0.0222	0.0075	0.0075	0.1366	0.0107
SPMP	kg	1.093	1.079	0.381	0.662	0.712	0.427	0.419	0.009	0	3.292	0.707	0.003	0	1.132	0.243
SO2	kg	0.365	0.256	0.163	0.206	0.246	0.192	0.181	0.006	0	2.169	0.289	0.002	0	0.746	0.099
NOx	kg	0.283	0.534	0.171	0.197	0.340	0.188	0.189	0.002	0	1.112	0.321	0.001	0	0.382	0.111
CO	kg	0.261	0.121	0.078	0.183	0.096	0.020	0.014	0.000	0	0.636	0.044	0.000	0	0.219	0.015
Energy Resource Consumption																
Hydro-electricity	kWh	0.01	0.01	2.98	0	0.02	11.3	6.02	0	612	0	0	0	211	0	0
Wind Power	kWh	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Coal	kg	0	0	0	0	0	0.01	0	0	0	0.26	0	0	0	0.09	0
Uranium	grams	0.0002	0.0002	0.090	0.0001	0.0005	0.34	0.18	10.4	0	0	0	3.57	0	0	0
Natural Gas	m3	0	0	57.9	0	93.3	57.1	60.8	0	0	0	111	0	0	0	38.1
Crude Oil	l	99.4	68.1		56.2	0	0	0	0	0	0	0	0	0	0	0

Table C.4 Modelling Results for Vancouver Bus Scenarios

Stressor Category	Units	12 Diesel ICE	13 NGV	14 H2 FCV - Decentralized SMR	15 H2 FCV - Centralized SMR	16 H2 FCV - Hydroelectricity Electrolysis	17 H2 FCV - Natural Gas Electrolysis	18 EV - Hydroelectricity	19 EV -Natural Gas
Air Emissions									
GHG	kg CO2eq	1925	2023	1447	1546	0	3121	0	1169
ADP	kg SO2eq	14.697	9.346	2.811	3.009	0.000	5.660	0.000	2.121
GLOP	kg	20.253	12.325	2.031	2.177	0.000	4.102	0.000	1.537
PM	kg	0.2026	0.0358	0.0272	0.0269	0.0231	0.1360	0.0232	0.0655
SPMP	kg	23.002	14.372	3.809	4.079	0.000	7.685	0.000	2.879
SO2	kg	2.749	2.047	1.779	1.902	0.000	3.553	0.000	1.331
NOx	kg	17.167	10.487	1.483	1.591	0.000	2.945	0.000	1.103
CO	kg	2.482	3.405	0.083	0.089	0.000	0.535	0.000	0.200
Energy Resource Consumption									
Hydro-electricity	kWh	0.29	188	603	320	7976	0	2990	0
Natural Gas	m3	0.01	785	684	731	0	1360	0	510
Crude Oil	l	741	0	0	0	0	0	0	0

Table C.5 Modelling Results for Calgary Bus Scenarios

Stressor Category	Units	33 Diesel ICE	34 NGV	35 H2 FCV - Decentralized SMR	36 H2 FCV - Centralized SMR	37 H2 FCV - Coal Electrolysis	38 H2 FCV - Natural Gas Electrolysis	39 H2 FCV - Wind Electrolysis	40 EV - Coal	41 EV - Natural Gas	42 EV - Wind
Air Emissions											
GHG	kg CO2eq	1921	2148	1983	1812	8099	3094	0	3034	1159	0
ADP	kg SO2eq	14.615	9.904	5.037	4.108	32.644	7.010	0	12.230	2.626	0
GLOP	kg	20.144	12.402	2.898	2.515	14.846	6.029	0	5.562	2.259	0
PM	kg	0.1949	0.0679	0.1307	0.0819	1.4448	0.1387	0.0231	0.5558	0.0665	0.0232
SPMP	kg	22.887	14.956	6.308	5.284	37.273	9.668	0	13.965	3.622	0
SO2	kg	2.743	2.554	3.409	2.769	22.428	3.639	0	8.403	1.363	0
NOx	kg	17.058	10.561	2.339	1.923	14.678	4.844	0	5.499	1.815	0
CO	kg	2.458	3.576	0.634	0.382	7.577	0.548	0	2.839	0.205	0
Energy Resource Consumption											
Hydro-electricity	kWh	0.01	7.46	24.0	12.8	0	0	0	0	0	0
Wind Power	kWh	0	0	0	0	0	0	7706	0	0	2887
Coal	kg	0	0.10	0.32	0.17	4.43	0	0	1.66	0	0
Natural Gas	m3	0.01	785	683	731	0.00	1395	0	0	523	0
Crude Oil	l	741	0	0	0	0	0	0	0	0	0

Table C.6 Modelling Results for Toronto Bus Scenarios

Stressor Category	Units	58 Diesel ICE	59 NGV	60 H2 FCV - Decentralized SMR	61 H2 FCV - Centralized SMR	62 H2 FCV - Nuclear Electrolysis	63 H2 FCV - Hydroelectricity Electrolysis	64 H2 FCV - Coal Electrolysis	65 H2 FCV - Natural Gas Electrolysis	66 EV - Nuclear	67 EV - Hydroelectricity	68 EV - Coal	69 EV - Natural Gas
Air Emissions													
GHG	kg CO2eq	1945	2197	1678	1713	19	50	7069	3280	7	19	2648	1229
ADP	kg SO2eq	15.103	9.980	3.904	3.780	0.094	0	35.522	6.246	0.035	0	13.309	2.340
GLOP	kg	20.785	12.994	2.828	2.872	0.029	0	13.567	5.016	0.011	0	5.083	1.879
PM	kg	0.2401	0.0643	0.1190	0.0758	0.0233	0.0231	4.5546	0.1340	0.0232	0.0232	1.7210	0.0647
SPMP	kg	23.569	15.210	5.150	5.063	0.103	0	39.746	8.535	0.039	0	14.891	3.198
SO2	kg	2.784	2.216	2.321	2.190	0.075	0	26.179	3.489	0.028	0	9.808	1.307
NOx	kg	17.699	11.154	2.273	2.283	0.027	0	13.425	3.880	0.010	0	5.030	1.454
CO	kg	2.596	3.453	0.240	0.172	0.005	0	7.683	0.525	0.002	0	2.879	0.197
Energy Resource Consumption													
Hydro-electricity	kWh	0.06	42.5	137	72.7	0	7389	0	0	0	2768	0	0
Wind Power	kWh	0	0	0	00	0	0	0	0	0	0	0	0
Coal	kg	0	0.02	0.06	0.03	0	0	3.17	0	0	0	1.19	0
Uranium	grams	0.0019	1.28	4.11	2.19	125	0	0	0	47.0	0	0	0
Natural Gas	m3	0.01	787	689	734	0	0	0	1337	0	0	0	501
Crude Oil	l	741	0	0	0	0	0	0	0	0	0	0	0

Appendix D – Economic Assumptions

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Table D.1 Assumptions for Calculating Hydrogen Delivered Costs ($ in Canadian)

	Centralized Reformer	Decentralized Reformer	Decentralized Electrolysis
Natural Gas Prices ($/GJ)	3.9 – BC 2.3 – Alberta 4.3 - Ontario	5.6 – BC 3.7 – Alberta 5.0 - Ontario	N/A
Off Peak Electricity Price ($/kWh)	0.045	0.045	0.045
Reformer/Electrolyzer Efficiency (HHV)	73% (NG only)	73% (NG only)	79%
Production (kg/day)	35,000	1,200	1,200
Capacity factor	0.9	0.8	0.8
Average distance between central plant & stations	25	N/A	N/A
Capital Costs[A] ($ millions)	50	4	3.5
Operating Costs (excluding Natural Gas & Electricity) ($ millions)	1	0.08	0.07
Station Capital Costs ($ millions)	30	Included in Capital Costs	Included in Capital Costs
Station Operating Costs ($ millions)	0.6	Included in Operating Costs	Included in Operating Costs
Compressor Capital Costs ($ millions)	4.7	Included in Capital Costs	Included in Capital Costs
Compressed Hydrogen delivery cost ($/kg)	0.4	N/A	N/A
Liquefier Capital Costs ($ millions)	63	N/A	N/A
Liquefied Hydrogen transportation cost ($/kg)	0.68	N/A	N/A
Energy Required for H_2 compression (MJ per MJ)	0.05 (gaseous H_2), 0.30 (liquid H_2)	0.05	0.05
Return on Investment (after tax, real rate of return)	10%	10%	10%
Average Corporate Tax Rate[B]	26%	26%	26%
Depreciation Recovery Period (years)	15	15	15
Inflation Rate	1.5%	1.5%	1.5%
Overall Hydrogen Cost (CAN$/kg)	2.4 – BC (4.1 liq.) 2.2 – Alberta (3.8 liq.) 2.5 – Ontario (4.2 liq.)	3.1 – BC 2.8 – Alberta 3.0 - Ontario	4.1

A. Assumes equipment production volumes greater than 1000 units.

B. Average corporate tax rate is not the marginal tax rate but is the ratio of taxes to positively adjusted profits for 1993, the most recent year of data. This measure better represents the rate of tax actually paid after accounting for deductions and tax credits.

Table D.2 Fuel Costs

	Units	Vancouver	Calgary	Toronto
Gasoline[A]	CAN$ / l	0.556	0.524	0.590
Diesel[A]	CAN$ / l	0.533	0.486	0.509
Natural Gas[A]	CAN$ / kg	0.536	N/A	0.589
Electricity – residential[B]	CAN$ / kWh	0.0675	0.0804	0.0988
Methanol[C]	US$ / gallon	0.34 + distribution cost + taxes		
Electricity – Time-of-use rate[D]	CAN$ / kWh	0.045		
Electricity – Off-peak	CAN$ / kWh	0.0355		

N/A = not available from the source cited

A. 1999 average [*Energy Statistics Handbook*, Statistics Canada, Oct. 2001]

B. Rates effective May 1, 1999 ["Comparison of Electricity Prices in Major North American Cities – Rates Effective May 1, 1999," Hydro Quebec, 1999]

C. Estimated retail price of methanol. Based on 1999 average wholesale cost of US$0.34 / gallon in the United States. [Methanex website: www.methanex.com/investorcentre/presentations/methanex1101.pdf]

D. Estimated based on time-of-use rates available from BC Hydro (1999), Utilicorp, and Brampton Hydro. Assumes electricity is used equally during peak and off-peak hours.

Table D.3 Cost Estimates for Vehicle Components Mass Produced in High Volumes

Component	Units	High estimate	Low Estimate
Fuel cell system	US$ / kW	100	50
Motor and controller	US$ / kW	26	13
Extra structural support	US$ / kg	1	1
Hydrogen storage cylinder rated @ 5000 psi	US$	1000	500
Fuel processor system	US$ / kW	25	15
Cost of 12 kg methanol tank	US$	100	100
Gasoline ICEV drivetrain, fuel tank, electrical system and emission control system	US$ / kW	39	39

Source: Ogden 1997

Table D.4 Cost Estimates for Equivalent Mass Produced Vehicle Systems[A]

Vehicle	Power (kW)	Vehicle mass (kg)	High(US$)	Low (US$)
NECAR 4a	53	1514	$8,027	$4,188
NECAR 5	55	1700	$8,940	$4,925
Ford Focus	82	1165	$3,198	$3,198

A. Vehicle systems are based on vehicle components listed in previous table.

Table D.5 Approximate Costs for Buses

	Units	Fuel Cell Bus	Diesel Bus[A]	Natural Gas Bus[A]	Electric Trolley Bus[A]
Approx. capital cost	CAN$	Unknown	331,000	390,000	800,000
Approx. operating cost	CAN$	Unknown	0.45 / km	0.76 / km	28,000 / yr

A. Coast Mountain Bus Company, Gary L. Hinz, Director, Maintenance Engineering, Training, and Standards