CAN HYDROGEN WIN?:
EXPLORING SCENARIOS FOR HYDROGEN
FUELLED VEHICLES

by

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ABSTRACT

This study explored the conditions under which hydrogen might succeed in Canada’s transportation sector in a carbon-constrained world. Long-run simulations were created using CIMS, a hybrid energy-economy model that is technologically explicit, behaviourally realistic, and incorporates drivers of technological change. A hydrogen supply submodel was built to simulate economies of scale in infrastructure. Capital costs, technology performance, infrastructure, fuel prices, and other conditions were varied in the simulations. All scenarios included a carbon tax and a vehicle emission standard that mandated a minimum market share for zero- and near-zero emission vehicles. Hydrogen was found to gain less market share than other options such as biofuel plug-in hybrids, but did well when biofuels were removed or priced excessively. Hydrogen fuel cells failed unless costs were assumed to descend independent of demand. However, hydrogen vehicles were shown to have little environmental advantage over other zero- and near-zero emission vehicles.

Keywords: hydrogen vehicles; zero-emission vehicles; technological change; transportation scenarios; hydrogen production; energy-economy modelling

Subject Terms: Transportation, Automotive -- Environmental aspects; Hydrogen as fuel -- Economic aspects; Technological innovations -- Environmental aspects; Climatic changes -- Government policy; Economic forecasting; Climatic changes -- Mathematical models
Dedicated to my dad,

who fostered my impulse to ask ‘why’
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## GLOSSARY

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>CCS</td>
<td>CO$_2$ capture and storage</td>
</tr>
<tr>
<td>CO$_2$e</td>
<td>Carbon dioxide equivalent. This is a unit which allows various greenhouses gases to be combined into a single measure based on their potency in causing global warming relative to CO$_2$.</td>
</tr>
<tr>
<td>endogenous</td>
<td>Produced from within. For example, in energy-economy modelling, an endogenous hydrogen price means that the price is determined by factors within the model, rather than being externally specified.</td>
</tr>
<tr>
<td>exogenous</td>
<td>Produced from outside. In other words, externally specified.</td>
</tr>
<tr>
<td>HFCPHEV</td>
<td>Hydrogen fuel cell plug-in hybrid electric vehicle</td>
</tr>
<tr>
<td>HFCV</td>
<td>Hydrogen fuel cell vehicle</td>
</tr>
<tr>
<td>HICEV</td>
<td>Hydrogen internal combustion engine vehicle</td>
</tr>
<tr>
<td>NZEV</td>
<td>Near-zero emission vehicle</td>
</tr>
<tr>
<td>PHEV</td>
<td>Plug-in hybrid electric vehicle</td>
</tr>
<tr>
<td>PHEV40</td>
<td>An extended-range gasoline hybrid plug-in vehicle. The ‘40’ refers to the number of miles that can be travelled on the battery alone, without gasoline. See Simpson (2007) for more details.</td>
</tr>
<tr>
<td>SMR</td>
<td>Steam methane reforming (reforming of natural gas)</td>
</tr>
<tr>
<td>VES</td>
<td>Vehicle emission standard</td>
</tr>
<tr>
<td>ZEV</td>
<td>Zero-emission vehicle</td>
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CHAPTER 1: INTRODUCTION

As the evidence of human-induced climate change has mounted (IPPC, 2007), governments and individuals across the globe have sought out ways to reduce greenhouse gas emissions. In Canada, the federal government has committed to reducing emissions 60-70% from 2006 levels by 2050 (NRTEE, 2007), and has drafted an industrial cap-and-trade system that will start us down the road to a lower-emission economy. A number of provinces have implemented or announced plans for their own jurisdictions to reduce emissions.¹

Meeting these targets is not an easy task. Efforts to reduce emissions through behaviour change have met with resistance from consumers (Poortinga et al., 2003) and had mixed success (Jaccard et al., 2004). In the transportation sector, for instance, drivers are very reticent to abandon their cars in favour of transit, biking, or walking (Horne, 2003). A more promising route might be to employ technologies which reduce emissions while maintaining the same level of service (such as kilometres travelled in your car, or warmth in your home).

¹ Alberta adopted an intensity-based cap-and-trade system in 2007; British Columbia has a carbon tax that took effect in July 2008, and is drafting a cap-and-trade system with the Western Climate Initiative, a body that includes Manitoba, California, Arizona, Washington, Oregon, Montana, New Mexico and Utah. Quebec and Ontario recently announced that they will be creating an absolute cap-and-trade system together.
This study looks at technological change in the transportation sector. This sector’s emissions are both significant—accounting for 26% of greenhouse gas emissions in Canada (Environment Canada, 2008)—and difficult to reduce because of a number of obstacles. Any new vehicle technologies must meet particularly demanding requirements in terms of portability, performance, safety, and convenience. And they must compete against conventional vehicles that tap into an already-established network of fuelling stations. Nevertheless, to meet the long-term emission targets set by governments, the long-term requirement is likely to include a key role for zero-emission vehicles.

Hydrogen fuel cell vehicles have been touted as the solution to this zero-emission challenge (e.g. Clark & Rifkin, 2006; Dunn, 2002; Industry Canada, 2003; McDowall & Eames, 2006). Given the profound changes such a transition would create in our society, in this study I explore the validity of these claims. More specifically, I compare the viability of hydrogen vehicles against their zero- and near-zero emission competitors, while taking into account potential cost reductions, infrastructure and acceptance in the marketplace. Using CIMS, an energy-economy model, I simulate the competition between these vehicles in Canada over a 45-year timeframe. Because of the enormous uncertainties in these technologies and in future circumstances, I ran forty-three different simulations. Each simulation scenario had one or more factors altered, allowing me to explore the
conditions under which hydrogen may or may not succeed as an energy carrier in the transportation market. All scenarios applied the same rigorous policy regime—a carbon tax combined with a market share mandate for zero- and near-zero emission light duty vehicles. These policies pushed emission reduction throughout the economy while targeting technological innovation for cars and light-duty trucks. By applying the same policy regime to all scenarios, my study was able to focus on the key factors determining the success of hydrogen, rather than the efficacy of the policies themselves.

This chapter gives an overview of the issues driving my research. Section 1.1 defines zero emission vehicles and provides background on the origin of the concept and its role in combating climate change. Section 1.2 presents some of the issues surrounding fuel emissions, and section 1.3 discusses the pros and cons of the vehicles considered in this study. I then talk about the dynamics of technological innovation in section Technological Change, Path Dependency, and Policy and in section 1.5 I show how these can be simulated in a model. I finish with an elaboration of my research objectives.

1.1 What is a Zero-Emission Vehicle?

In this study I define zero-emission vehicles (ZEVs) as either (a) those with no tailpipe emissions of greenhouse gases, or (b) those running entirely with biofuel (a fuel produced from a biological source). In the latter case, this
is because the carbon released during combustion is the same carbon originally absorbed from the air by the plant used to make the fuel.

The concept of a zero-emissions vehicle was enshrined in California under its 1990 ZEV mandate, but was originally focused on the emission of air pollutants rather than greenhouse gases (Kemp, 2005). Plagued by persistent air quality issues, state lawmakers decided that the solution lay not in incremental increases in vehicle efficiency but in a dramatic redesign of auto systems. They had in mind an eventual transition to electric vehicles. At its core, the concept of a zero-emission vehicle entails transferring air pollution away from its point of use (usually in heavily polluted urban areas) towards the point of power production instead. California lawmakers felt this was justified because (a) centralized power production facilities had to meet stringent emission requirements, and (b) the electrical grid already had a relatively clean fuel mix (Kemp, 2005).

However, the focus of this study is greenhouse gases, not air pollutants. Greenhouse gases are not a local problem, but a global one, and as such the point of release makes no difference to the environment. And yet the principle of displacing emissions still applies because at the point of energy production there are potentially superior technologies for dramatically reducing or eliminating emissions altogether. The perfect 'zero-emission' vehicle would have zero fuel cycle emissions, which is to say zero tailpipe
emissions, and zero emissions during production and transport of the energy source (such as electricity or hydrogen).\textsuperscript{2}

1.2 Fuel Cycle Greenhouse Gas Emissions

Electricity, hydrogen, and biofuels are not sources of energy, but rather ‘energy carriers’. In other words, other energy primary sources such as wind, hydro, biomass, natural gas, or coal, are needed to produce them. To have zero fuel cycle emission means they must be produced and transported without greenhouse gas (GHG) emissions.

For biofuels, this means that the cultivation of biomass has no emissions throughout the entire chain of production—for instance, no use of fossil fuels in tractors, no GHGs generated by fertilizers and pesticides, and no release of GHGs from cultivated soil. There must be no emissions from operations converting biomass into ethanol or biodiesel, or from transportation to the fuelling station.

For electricity, production must use either renewable sources, such as wind or hydro, or employ fossil fuels with CO$_2$ capture and storage technologies. Similarly, hydrogen can be made by stripping the oxygen molecule from water (electrolysis) using zero-emission electricity. Or it can be

\begin{itemize}
\item\textsuperscript{2} Fuel cycle emissions include the net emissions from production, transportation, and use of the energy carrier, measured in tCO$_2$e/vehicle kilometre travelled. This is also known as the 'well-to-wheel' emissions. 'Life cycle' emissions also include emissions from the manufacture of the vehicle, which is outside the scope of this analysis.
\end{itemize}
reformed from hydrocarbons such as natural gas or coal, coupled with CO₂ capture and storage.

CO₂ capture and storage (CCS) is a technology that could allow us to use fossil fuels without the negative impacts from air pollution and greenhouse gas emissions. On a global scale it has been proposed as an important tool in the arsenal against climate change (IPCC, 2005). It involves removing CO₂ from the flue stream of point source emitters such as power plants, and injecting the gas deep underground into depleted oil and gas reservoirs, unmineable coal seams, and saline aquifers (IEA GHG R&DP, 2001). The technology is being employed at a number of oil and gas operations around the globe, including Saskatchewan, Alberta, Norway, and Algeria (IPCC, 2005). Although there are a few low-probability risks such as asphyxiation from major leaks, seismic triggering, and potable water contamination, experts are on the whole confident that the risks of underground injection are low. This is supported by a long history of acid gas injection in depleted reservoir sites in Canada (Keith, 2002). However, in order for CCS to meet the objective of reducing emissions, storage sites must retain the injected gases for thousands of years. To meet this objective, geological storage sites need to be selected with great care and monitored over the long term.

Today, there is much debate about whether zero-emission vehicles actually reduce emissions. None of the energy carrier options have, in
practice, zero fuel cycle emissions. Nevertheless, they could be worthwhile if their net effect is to reduce emissions. Figure 1-1 on the next page summarizes a number of studies on fuel cycle emission reductions from various internal combustion engine vehicles (ICEV), hydrogen fuel cell vehicles (HFCV) and battery electric vehicles (BEV). All ZEVs should be compared against less costly options such as current gasoline hybrids, also shown in Figure 1-1.

An important message of this figure is that fuel cycle emission estimates vary greatly based on the type of primary energy source used, the development status of the technology, and the study assumptions. I've juxtaposed Wang's study, which uses estimates of 2010 technologies, with Delucchi's study, which predicts the status of technologies in 2050. Even within the same study, varying assumptions generate differences: Wang's 'high emission' hydrogen is liquefied hydrogen made with average U.S. grid electricity (liquefying hydrogen requires more energy than simply compressing it), 'mid emission' hydrogen is from centralized natural gas production, 'low emission' hydrogen is generated through electrolysis with renewable electricity. Delucchi's 'high emission' hydrogen is made from natural gas, 'mid emission' hydrogen is surprisingly from coal, and 'low emission' hydrogen is from hydropower. The dramatic differences between Delucchi's estimate of ethanol vehicle emissions and the other study,
Figure 1-1: Fuel Cycle Greenhouse Gas Emission Reduction Impacts for Energy Carriers (relative to a conventional gasoline vehicle)³

³ 'Other Studies' are: Searchinger et al. (2008) for the ethanol cars; EPRI&NRDC (2007) for gasoline hybrid and gasoline hybrid plug-in; Ogden (2004) for the hydrogen fuel cell vehicles.
Searchinger et al. (2008), is due to the latter’s inclusion of emissions caused by land use changes—although the use of marginal cropland would improve reductions. One way of avoiding generating the ‘negative emission reductions’ shown is to impose emission criteria on ethanol generation, such as those in the US Renewable Fuels Standard (Mazza, 2008).

Other things to note—in this graph, Delucchi’s ethanol cars are using E90 fuel, ‘high emission’ electricity is generated with coal, and ‘low emission’ electricity is from hydropower. The emissions for hybrid plug-in emissions, from EPRI&NRDC (2007) are based on extended range gasoline plug-ins (PHEV40) using a medium emission scenario for California grid electricity. No studies on biofuel plug-in hybrids were available, but the reductions would be somewhere between those of ethanol vehicles and electric vehicles.

In addition to the direct emission impacts of the ZEVs, there are other relevant issues to fuel choice not addressed directly in this study. For example, given limited land and water resources, biofuels may not be capable of displacing fossil fuels entirely (MacLean & Lave, 2003). Similarly, producing hydrogen from water (through electrolysis) may not be sustainable in a world facing increased competition for scarce fresh water resources (Bossel, 2006). Although hydrogen vehicles do produce clean water as an exhaust product, this water is dispersed and therefore less useful for scale application.
Producing hydrogen from imported natural gas also does not address energy security concerns (NRC, 2004). From a cost effectiveness perspective, many analysts have pointed out that it costs less to reduce CO₂ by using electricity and natural gas to reduce grid emissions, than to use them for producing hydrogen for fuel cell vehicles (Keith & Farrell, 2003; Eyre et al., 2002; Hammerschlag & Mazza, 2005; Simbeck, 2006). However hydrogen could also facilitate greater use of intermittent renewable resources, because of its ability to be stored (Converse, 2006).

There are ways of ensuring that ZEVs do have significant emission-reduction impacts. One is to attach fuel cycle emission criteria, such as in the US Renewable Fuels Act. Another is to attach a price to carbon throughout the economy, the approach I've used in this study.

1.3 Status of Zero- and Near-Zero Emission Vehicles

1.3.1 Hydrogen Vehicles

Hydrogen fuel can power a vehicle using an internal combustion engine, similar to gasoline, or in a hydrogen fuel cell. A fuel cell converts the energy released from a chemical reaction directly into electric power (Swisher, 2005). A third type of vehicle is also possible—hydrogen fuel cell hybrid plug-ins. This vehicle is fuelled with both hydrogen (used to produce electricity via a fuel cell) and electricity from the grid.
Hydrogen internal combustion vehicles (HICEVs) release no GHGs and only a small amount of NOx, an air pollutant. Hydrogen fuel cell vehicles (HFCVs) release neither, and have an on-board energy efficiency double that of gasoline ICE vehicles.

All HFCVs and battery electric vehicles have electric drivetrains, which ensure low maintenance costs, quiet operation, and greater manufacturing flexibility (NRC, 2004). They have the added benefit of being able to provide remote power for appliances and electronics. If they are designed with plug-in abilities, these vehicles could connect to the grid when not in use and provide supplemental power during peak demand periods (Williams & Kurani, 2007).

Hydrogen vehicles have similar refuelling requirements to gasoline vehicles. Manufacturers plan to make a fill-up last several hundred kilometres (Kalhammer et al., 2007). However, they are having difficulty achieving this target. Developers do not foresee fuel tanks costing less than US$2000/vehicle even with mass production (Kalhammer et al., 2007). Compare this with a conventional gasoline tank, which costs US$125 (Ogden, 2004). At the 700 bar compression level considered by most vehicle manufacturers, a hydrogen tank will take up about four times the space of a gasoline tank with equivalent range (Romm, 2003), leaving less room for passengers and storage. While manufacturers are considering modifying vehicle designs to accommodate the tank more readily, the extra weight
cannot be avoided. Novel methods for onboard hydrogen storage are being investigated but the technologies are too immature to make any predictions about cost and performance (Kalhammer et al., 2007).

Other key components also require significant improvement before HFCVs can be commercialized. Fuel cell systems are one of the largest additional costs associated with hydrogen vehicles. Developers’ estimates of costs with high-volume production vary between US$80/kW and US$600/kW (Kalhammer et al., 2007)—this would translate into a cost of between about Cdn$5000 and $37,000 for the fuel cell system alone (Thomas, 1998). In contrast, the US FreedomCAR has set a goal of 35$US/kW (about Cdn$2000 in total) by 2015 for fuel cells to be competitive. There is still a long way to go. Durability issues will also need to be resolved. Demonstration vehicles have shown a fuel cell lifetime of only 2-3 years, a number that needs to be extended to at least 15 years to appeal to consumers (Kalhammer et al., 2007).

Safety is a large concern with hydrogen vehicles. Hydrogen is more flammable than gasoline and has a lower ignition temperature—low enough to be ignited by a spark from the static charge of a cell phone (Romm, 2003). Although hydrogen leaks diffuse quickly into the air and are non-toxic, in confined spaces this creates a larger volume of combustible mixture. A hydrogen leak is both colorless and odourless, and a flame from burning hydrogen is invisible (Kalhammer et al., 2007). As a result, hydrogen leaks
are highly dangerous. Any fuel handling by the general public will require further safety innovations, and strict codes and regulations.

Hydrogen vehicles also face a "chicken and egg" problem—vehicles will not be bought unless there are hydrogen fuelling stations, but fuelling stations will not be built unless there are hydrogen vehicles on the road.

1.3.2 Battery Electricity Vehicles

Battery electric vehicles (BEVs) have many of the same advantages of hydrogen fuel cells with fewer unknowns around safety and technology cost. The main challenge with battery-only electric vehicles is the limited distance they can travel on one charge and the time required to recharge. Batteries are still very costly (Simpson, 2006), and the larger the range, the larger (and more expensive) the battery must be. As a result, electric vehicles have been primarily built as smaller-range, limited speed vehicles for use within gated communities, campuses and other small areas (Larrue, 2003).

A more immediately viable technology is the gasoline-electric hybrid, which runs on gasoline but uses an electric drivetrain. These vehicles consume less fuel than equivalent models and emit fewer greenhouse gases. Plug-in hybrids, which are gasoline-electric hybrids with larger batteries partially fuelled with grid electricity, reduce emissions still further. Experts anticipate that as the technology matures, larger onboard batteries will allow these vehicles to have a significant range using only electricity, with gasoline acting as a backup fuel for longer trips (Kalhammer et al., 2007).
Plug-in batteries can be combined with other vehicle technologies to produce zero-emission vehicles. If gasoline is replaced with ethanol or biodiesel, the resulting biofuel plug-in electric vehicle becomes a ZEV. Similarly, plug-in technology can be combined with hydrogen combustion engines or hydrogen fuel cells. This latter combination, the hydrogen fuel cell plug-in hybrid vehicle, could also lower the cost of the fuel cell, as the battery combination reduces performance requirements for the fuel cell alone (Kalhammer et al., 2007).

Battery technology is undergoing considerable development, with plans by a number of major car companies to release plug-in hybrid models by 2010. Manufacturers, however, are facing hurdles in developing suitable battery technology. Current hybrid vehicles employ nickel-metal hydride batteries, which have proven performance characteristics and a 10-15 year lifetime. Their cost, however, is not expected to reduce much further (Kalhammer et al., 2007), and manufacturers are now looking to lithium ion batteries for the next generation of hybrids and plug-ins. These batteries will ultimately have a lower cost with equivalent or superior capabilities. A primary concern, however, is that some lithium ion chemistries are susceptible to rupture and can vent flammable gases. Manufacturers have been working on designs to prevent such events, and expect to commercialize the technology in 2008 (Kalhammer et al., 2007).
Plug-in hybrids and battery-only electric vehicles don’t have the same “chicken and egg” problem around fuelling infrastructure as hydrogen and biofuel options, since vehicles can simply be plugged in to a standard electrical socket. Nevertheless, users would have to adapt to the routine of plugging their cars in at night, and as such the vehicles have an ‘intangible cost’ that could disappear as the technology gains acceptance (Axsen, 2006b).

1.3.3 Biofuels

Fuels produced using biomass have similar properties to fossil fuels and thus require fewer vehicle adjustments than electricity or hydrogen. Because these fuels in their pure form can create problems during cold weather operation, they are generally blended with gasoline (US DOE, 2008). This study primarily considers E85 ethanol, a blend of 85% ethanol with 15% gasoline. Because of the fuel’s fossil fuel component, this study considers E85 ethanol vehicles to be near-zero-emission rather than zero-emission. It’s also worth noting that biofuel combustion generates many of the same air pollutants as fossil fuels (MacLean & Lave, 2003).

Another downside of E85 is that it has 27% less energy content per volume than gasoline (US DOE, 2008). Fuelling station availability is also a concern in the short term, and for this reason several manufacturers are currently producing ‘flex-fuel’ vehicles which can run on both E85 and gasoline.
1.3.4 Summary

Table 1-1 summarizes some of the technical and cost issues mentioned for each vehicle. Only two are available now—the conventional gasoline hybrid electric vehicle, and the ethanol vehicle—while the rest are anticipated to be available in a few years, with hydrogen fuel cells likely taking the longest to come to market. All ZEVs and NZEVs are more costly than a conventional hybrid, with hydrogen fuel cell vehicles being the most costly at least to begin with. Any vehicles using biofuel or hydrogen face issues with refuelling infrastructure. However, biofuels have the advantage in that they can be gradually mixed in to the gasoline supply, and in ‘flex-fuel’ engines can be substituted with gasoline where biofuel is not available. Battery-only electric vehicles have limited range, while plug-in hybrids overcome this problem by allowing gasoline or biofuel to act as a backup. Safety is primarily a concern with vehicles using hydrogen, which will require significant advances in technology and safety procedures in order to become successful.

1.4 Technological Change, Path Dependency, and Policy

While technological change is clearly important to progress in sustainability, predicting the performance and cost of technologies is problematic. In addition to uncertainties around a technology’s potential, there are also complex market dynamics which can strongly influence a technology’s advancement. Technology competitions involving economies of
Table 1-1: Summary of Technical and Cost Issues for Zero- and Near-Zero Emission Vehicles

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Range and Refuelling</th>
<th>Cost &amp; Availability</th>
<th>Safety</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline hybrid electric</td>
<td>Better range than conventional gasoline.</td>
<td>Costlier than conventional car; available now.</td>
<td>No problems.</td>
<td>Not a ZEV but good value for the tailpipe reductions; no consumer drawbacks.</td>
</tr>
<tr>
<td>Biofuel plug-in hybrid [ZEV]</td>
<td>Simple plug-in. Electric range for shorter trips, biofuel for longer trips (may be fuel availability issues).</td>
<td>Considerably costlier than conventional car; available date uncertain, possibly 2010.</td>
<td>Some battery safety issues to overcome.</td>
<td>A ZEV with few consumer drawbacks; biofuel availability may be a problem.</td>
</tr>
<tr>
<td>Battery-only electric [ZEV]</td>
<td>Simple plug-in. Limited range, requires overnight charging.</td>
<td>Very costly; available date uncertain, possibly 2015.</td>
<td>Some battery safety issues to overcome.</td>
<td>Cost is a barrier; range issues.</td>
</tr>
<tr>
<td>E85 Ethanol [NZEV]</td>
<td>27% smaller range unless larger tank; currently fuel availability issues unless vehicle is ‘flex-fuel’.</td>
<td>Costlier than conventional car; available now.</td>
<td>No problems.</td>
<td>Not a ZEV but good value for the tailpipe reductions; few consumer drawbacks; biofuel availability may be a problem.</td>
</tr>
<tr>
<td>Hydrogen internal combustion engine [ZEV]</td>
<td>Smaller range than conventional gasoline unless bigger tank. Fuel availability issues.</td>
<td>Costlier than conventional car; available date uncertain, possibly 2015.</td>
<td>Leaks are dangerous. New technologies and safety codes required.</td>
<td>ZEV with technical and safety obstacles to overcome; fuel availability may be a problem.</td>
</tr>
<tr>
<td>Hydrogen fuel cell [ZEV]</td>
<td>Smaller range than conventional gasoline unless bigger tank. Fuel availability issues.</td>
<td>Potentially much costlier than conventional car; available date uncertain, possibly 2020.</td>
<td>Leaks are dangerous. New technologies and safety codes required.</td>
<td>ZEV with big technical, safety, and cost obstacles to overcome; fuel availability may be a problem.</td>
</tr>
<tr>
<td>Hydrogen fuel cell plug-in hybrid</td>
<td>Simple plug-in. Electric range for shorter trips, hydrogen for longer trips (may be availability issues).</td>
<td>Potentially much costlier than conventional car but less at first than pure HFCVs; available date uncertain, possibly 2020.</td>
<td>Leaks are dangerous. New technologies and safety codes required. Some battery safety issues to overcome.</td>
<td>ZEV with big technical, safety, and some cost obstacles to overcome; fuel availability may be a problem.</td>
</tr>
</tbody>
</table>
scale, particularly in infrastructure, are highly path-dependent. This means that if one technology gains a lead early on it may prevent other worthy technologies from succeeding. It may do so for a minor reason, such as being introduced a few years earlier, or having a better marketing budget. But once that technology gains market share, it can get “locked-in” (Arthur, 1994). The extensive network of gasoline fuelling stations, for instance, could preclude the adoption of even a cheap and superior vehicle that uses a different fuel. Because of this, government policy can sometimes play a role in pushing the market towards more optimal outcomes (Azar & Dowlatabadi, 1999). At the same time, market intervention involves considerable economic and political risk. Policymakers need to be well informed before committing themselves to such an action.

1.5 Energy-Economy Modelling

Energy-economy simulation models are often used to help policymakers assess options for achieving environmental objectives. They can be used to forecast future emissions trajectories and assess how the success of various technologies could impact these emissions. There are many models in use today, each with its own method of representing consumer behaviour, economic feedbacks, and technological change. Traditionally, energy-economy models could be divided into two categories: “Top-down” and “Bottom-Up” (Loschel, 2002).
"Bottom-Up" models are technologically explicit, containing detailed cost and performance characteristics of current and future technologies. These models are problematic in two ways. First, they look at financial costs but do not account for intangible factors that are an inherent part of consumer decisions, such as investment risk and personal preferences. Second, these models ignore macroeconomic feedbacks. Technologies which reduce energy use (and thus save money) can sometimes prompt spending on other energy-intensive goods and services (like flat-screen TVs), a phenomenon known as the 'rebound effect' (Greening et al., 2000). For these reasons, "bottom-up" models often overestimate the likely success of efficient or low-emission technologies, while underestimating the true costs of adopting environmental policies (Jaffe & Stavins, 1994).

"Top-down" models use aggregate historical data to model the relationship between energy and other economic inputs such as capital and labour. Technological change is simulated using two indices: the elasticity of substitution (ESUB) and the autonomous energy efficiency index (AEEI). ESUB is used to represent the substitution of inputs driven by price. The AEEI represents the non price-induced energy efficiency improvements in the economy. Because these parameters are derived from historical data, 'top-down' models have some behavioural realism. The first weakness of these models is that past behaviour is not necessarily an indicator of future behaviour in the long run (Grubb et al., 2002). Second, 'top-down' models lack
technological detail, so they cannot be used to simulate technology-specific policies (such as a vehicle emission standard), or examine the market penetration of a class of technologies, as is done in my study.

Recently, energy-economy modelling efforts have been aimed at marrying these two approaches together to gain the benefits of each (EIA, 2001; Greene et al., 2005). New ‘hybrid’ models seek to combine technological detail with behavioural realism and macroeconomic feedbacks (Bataille et al., 2006). CIMS is such a model. Housed at the Energy and Materials Research Group at Simon Fraser University, it aims to combine all three elements of a hybrid model. First, it includes cost, performance and energy use characteristics for over 3000 technologies throughout the Canadian economy. Second, it incorporates macroeconomic feedbacks by estimating the shifts in supply and demand caused by various emissions policies. And lastly, it incorporates behavioural realism by simulating the preferences and purchase decisions of consumers, based on empirical research.

CIMS is able to simulate technological change by incorporating two special functions. The first, the ‘learning-by-doing’ function, allows a new technology’s capital costs to decline with cumulative production. This relationship has been observed empirically throughout many markets (McDonald & Schrattenholzer, 2001). The second, the ‘neighbour effect’, allows intangible costs to decline with market share. These intangible costs are a valuation of consumer perceptions around quality, reliability,
availability, social desirability and other components not accounted for in the financial costs of a technology. Recent research has tried to gather values and dynamics for intangible costs in the vehicle market (Eyzaguirre, 2004; Mau, 2005; Axsen, 2006a).

CIMS has supply models for most of the major energy products—crude oil, refined petroleum, electricity, ethanol. This means that the price and quantity of these products change with consumer demand, and new technologies are adopted within these sectors as input prices alter and climate change policies are implemented. In other words, these energy prices are 'endogenous'. Prior to my study, however, CIMS lacked a supply model for hydrogen. The price of hydrogen was an input to the model, rather than a product of the model—i.e., it was 'exogenous'. By building a hydrogen production and transportation model, my research was able to simulate the interaction between supply and demand for this energy carrier. Specifically, I was able to model the price of hydrogen declining as demand increased, an effect caused by economies of scale in production and transportation infrastructure. I was also able to simulate the transition towards lower-emission production methods spurred by carbon taxation. These helped me to better model the potential adoption of hydrogen vehicles and the environmental impacts of this adoption.
1.6 Research Objectives

Policymakers, investors, engineers, and citizens across the globe have been grappling with the question of how we will propel ourselves in the future. Will hydrogen fuel our vehicles? The answer could have far-reaching consequences for emissions, energy production, urban infrastructure, and R&D investments. Using a scenario modelling approach, in this study I explore how various external forces and technological advances could affect the answer to this question.

My research objective is:

To explore the conditions under which hydrogen could succeed in a carbon-constrained world as a significant secondary energy carrier in the transportation sector.

The conditions I explore include:

- the rate of capital cost decline for hydrogen vehicles and competing vehicles
- the mature capital cost of these vehicles
- their performance and consumer acceptance
- the cost of hydrogen infrastructure
- the price of hydrogen, electricity and ethanol
- the availability of biofuels
- the availability of CO₂ capture and storage
- exclusion of near-zero-emission vehicles from the policy criteria

With a few exceptions, all scenarios include a rising carbon tax that reaches $330/tonne by 2035, and a vehicle emission standard (VES) requiring
that 30% of light-duty vehicles on the road be zero- or near-zero emission by 2035. The tax ensures that the entire economy (including fuel production) reduces emissions. The level mimics that supplied by the National Round Table for the Environment and Economy (2007) as the level required for Canada to achieve a 60% emission reduction without international emission credit purchases. The VES promotes the development of zero emission vehicle technologies without picking one technology over another.

Because policies are kept constant through all the scenarios, the focus is thus on external forces and technological advances that may affect hydrogen vehicle penetration, rather than on the efficacy of various policies in promoting hydrogen.

The remainder of this paper pursues these research objectives. Chapter 2 describes the model and the policy scenarios. Chapter 3 reports the simulation results. Chapter 4 summarizes the research, draws out potential insights, and comments on their relevance.
CHAPTER 2: METHODS

In this chapter, I begin by describing my general approach in this study. I then give a general overview of how the CIMS model works, and describe my additions to it. I then review the transportation sector and the attributes of vehicles included in this study. I briefly touch on the electricity and ethanol models as well. I end the chapter with a description of the policies applied throughout my simulations, and a list of the scenarios run.

2.1 General Approach

To simulate the market penetration of hydrogen vehicles under various future conditions, I employed the CIMS model and made a number of changes. First, I created a hydrogen supply sector, in order to endogenously determine a price for hydrogen that would reflect economies of scale and technological improvements through time. Second, I added some basic hydrogen-fuelled technologies to the industrial sectors. And third, I updated and added to the hydrogen vehicles within the transportation sectors.

I then ran the CIMS model repeatedly, keeping the policy constant while changing variables such as the future cost, performance and availability of technologies. This allowed me to explore which factors are most
likely to determine the success or failure of hydrogen vehicles in the marketplace.

Ultimately, I measure the success of hydrogen as an energy carrier in the transportation sector in terms of new market share among near-zero emission cars and trucks. However, I also look at the penetration among other vehicles and in the industrial sectors, at the decline in the price of hydrogen, and at total hydrogen production. The market share of various hydrogen production methods and the total greenhouse gas emissions are also presented.

### 2.2 Overview of the CIMS Model

#### 2.2.1 The Interaction of Demand and Supply

CIMS has three basic components: an Energy Supply and Conversion Model, an Energy Demand Model, and a Macroeconomic Model (Figure 2-1).

**Figure 2-1: CIMS Structure**
To begin a simulation, CIMS starts with an external forecast of economic growth that includes fuel prices and demand for energy services. The Energy Demand Model then calculates how much energy is required by the residential, commercial, transportation, and industrial sectors, while the Energy Supply and Conversion Model determines how to best supply these and at what price. CIMS iterates between the two models until a price-equilibrium is reached. The Macroeconomic Model calculates the effect of these changes in the costs of energy services and then on the demand for these services, and thus on economic growth and the structure of the economy.

CIMS divides Canada into 7 regions with 18 sectors (Table 2-1), and runs each separately (although there are some connections to reflect energy trade and globalized technology development).

2.2.2 Technology Competition

The type and quantity of energy demanded by each sector is determined by the technologies being used. In an industrial sector, for instance, water may be heated with a high-efficiency water heater or a low-efficiency water heater. In the transport sector, mobility may come from a gasoline car or a hydrogen car, for example.

The CIMS Energy Demand Model simulates the evolution of technology stocks in five-year increments from 2000 to 2050. A portion of the
technology stock retires every period based on its lifespan, while new technologies enter the stock to meet both demand growth and to replace retired stock. Using this method, the model creates a snapshot of the various technology vintages at any given time.

CIMS uses a technology competition function to capture the key factors affecting how consumers and industry make technology purchase decisions. The function calculates the market share of each type of technology purchased in each period. In Equation 1, market share is allocated between $K$ technologies where $MS_{jt}$ is the market share of technology $j$ relative to the set of $K$ technologies at time $t$. 

<table>
<thead>
<tr>
<th>Sectors</th>
<th>BC</th>
<th>Alberta</th>
<th>Sask.</th>
<th>Manitoba</th>
<th>Ontario</th>
<th>Québec</th>
<th>Atlantic</th>
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<tbody>
<tr>
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<td>Transportation Freight</td>
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<td>Crude Extraction</td>
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<td>Hydrogen</td>
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</tr>
</tbody>
</table>
where:

\[ MS = \frac{LCC_{\mu}}{\sum_{i=1}^{K} LCC_{\nu}^v} \]  

Equation 1

where:

MS = new market share

\[ v = \text{cost variance parameter} \]

LCC = life cycle cost as calculated by Equation 2:

\[ LCC_{\mu} = \left( CC_j \times \frac{r}{1 - (1 + r)^{-n}} \right) + MC_j + EC_j + i_j \]  

Equation 2

where:

CC = capital cost

MC = operating and maintenance cost

EC = energy cost

i = perceived intangible cost

r = perceived discount rate

n = technology lifespan

Three key behavioural parameters in the CIMS market share function have been determined through industry consultation and market research (e.g. Nyboer 1997, Rivers 2003, Axsen 2006a, Horne 2003). The perceived discount rate, \( r \), represents the trade-off consumers make between the present and the future. In many cases, this rate is much higher than a standard interest rate used, say, by a bank. In the transportation sector for instance, CIMS uses a 20% discount rate. A high discount rate suggests that consumers prefer technologies with a lower initial capital cost to those that promise future financial savings due to energy efficiency—a preference likely due to the greater risk of technological failure, higher transaction costs, and
loss of option value associated with new and unproven technologies. This generally penalizes energy efficient technologies.

The second behavioural parameter is \( i_j \), the perceived intangible cost of technology \( j \). When making purchases, consumers often have preferences for certain technology features that are unrelated to solely financial considerations. Some people, for instance, may prefer the quality of light from an incandescent bulb over that of a fluorescent bulb. A driver may choose a vehicle with more storage space or a greater acceleration capacity, even if a small economy car is cheaper. In CIMS, such preferences are accounted for by adding ‘intangible costs’ to a technology with less-than-preferred qualities.

The third behavioural parameter is \( v \), a variance parameter that reflects the fact that markets and human preferences are not homogenous. In the real world, no single technology gains 100% of new market share. In CIMS, the portion of new market share that goes to the “winning” technology is dependent on the cost difference between it and the next preferred technology, and on the cost sensitivity of firms and households. A technology that has vastly better life cycle costs than its nearest competitor will gain nearly all new market share, while a technology that has the same costs as its competitor will gain 50% of new market share.

### 2.2.3 Endogenous Technological Change

In Chapter 1, I emphasized the importance of modelling technological change endogenously. In CIMS, this is done by setting both capital costs and
intangible costs to decline with cumulative production and market share respectively.

**Learning-by-Doing**

The declining capital cost function, empirically based and widely accepted in the literature (Loschel, 2002), is shown in Equation 3:

\[
CC_j(t) = CC_j(t_0) \cdot \left( \frac{N(t)}{N(t_0)} \right)^{\log_{2} PR}
\]

where:
- \(CC_j(t)\) = capital cost of technology \(j\) at time \(t\)
- \(CC_j(t_0)\) = capital cost of technology \(j\) at the beginning of the simulation period (initial cost)
- \(N(t)\) = cumulative production of technology \(j\) up to but not including time \(t\)
- \(N(t_0)\) = cumulative production of technology \(j\) at the initial simulation period \(t_0\)
- \(PR\) = progress ratio representing the speed of learning\(^4\)

In CIMS, this equation has been modified to include an exogenous rate of decline, and a lowest possible cost, as in Equation 4:

\[\]

---

\(^4\) The progress ratio indicates how much costs decline for every doubling of cumulative production.
If
\[
\left( \frac{N(t)}{N(t_0)} \right)^{\log P_R} \cdot (1 - ERD)^{(t-t_0)}
\]
is greater than LPC, then:
\[
CC(t) = CC(t_0) \cdot \left( \frac{N(t)}{N(t_0)} \right)^{\log P_R} \cdot (1 - ERD)^{(t-t_0)}
\]
otherwise:
\[
CC(t) = LPC \cdot CC(t_0)
\]

where:

ERD = exogenous rate of development, as a percentage rate of decline per year
LPC = lowest possible cost, as a fraction of the initial cost, CC(t_0)

The exogenous rate of development is meant to represent capital cost declines that cannot be captured endogenously in CIMS, such as those generated through R&D investments and learning generated in other jurisdictions. Where possible, I avoided using the ERD as a mechanism for including learning in other jurisdictions, preferring instead to model it endogenously by assuming that their technology development and investment would mirror Canada’s because of similar circumstances and cost scenarios.

The ‘lowest possible cost’ is used to ensure capital cost declines do not fall below engineering estimates of minimal design and cost limits.
**Neighbour Effect**

The perceived intangible cost can also be set to decline with market share, based on the observation that consumer objections tend to decrease with a technology dissemination. CIMS uses the following function to represent this phenomenon:

\[
i_j(t) = i_{Fj} + \frac{i_j(t_0)}{1 + Ae^{kMS_j(t-1)}}
\]

where:

- \(i_j(t)\) = intangible cost at time \(t\)
- \(i_{Fj}\) = fixed intangible cost
- \(i_j(t_0)\) = initial variable intangible cost
- \(MS_j(t-1)\) = market share at time \(t-1\)
- \(A\) and \(k\) = parameters representing the shape of the curve and the rate of change in the intangible cost

While this function is consistent with technology diffusion theory (Rogers, 2003) it is not widely employed in energy-economy modelling. The \(A\) and \(k\) parameter values used are from recent empirical studies (Axsen, 2006a; Mau, 2005).

### 2.3 Hydrogen Production Model

CIMS previously lacked a hydrogen supply model, which meant hydrogen prices had to be specified exogenously, i.e. generated externally and then entered into the model as inputs. But the exogenous price would only be
accurate under specific circumstances because the price of hydrogen is highly dependent upon demand, technological developments and economies of scale that are determined by factors within the model. My task was to create a hydrogen supply model that would generate an endogenous fuel price. I tried to include enough production technologies to reflect the type of competition and technological evolution that could occur, without burdening future CIMS users with undue complexity.

2.3.1 Hydrogen Production Methods

My model includes five production methods:

1. Distributed steam methane reforming: Involves fuelling stations producing their own hydrogen onsite, using natural gas and steam.
3. Centralized steam methane reforming, with and without CO₂ capture: Involves processing natural gas, and possibly capturing 90% of CO₂ from the flue stream for transport and storage deep underground
4. Centralized coal gasification with electricity cogeneration, with and without CO₂ capture: Involves gasifying coal into synfuel, then extracting hydrogen. Byproducts are burned to produce a small amount of electricity, while 90% of CO₂ can be captured for transport and storage deep underground
5. Centralized biomass gasification, with and without CO₂ capture: Involves gasifying wood or other biomass to produce hydrogen.
90% of CO₂ can be captured for transport and storage deep underground, resulting in net negative emissions.5

In order to keep the model simple, I excluded a number of options that are common in other analyses (e.g. Greening, 2005; NRC, 2004):

- Coal gasification without cogeneration of electricity was removed when I found it was less competitive than the cogeneration version.
- Photobiological production of hydrogen using green algae has the potential to be exceptionally low-cost (Greening, 2005) but the chances of it becoming so appear small at present (Amos, 2004).
- Electrolysis using specific renewable resources was not included because renewable resources are included in detail in the CIMS electricity model. Instead, electrolysis options are represented more generally with the ‘decentralized grid electrolysis’ production method. Under strong policy signals such as those in my analysis, a large portion of new electricity production is renewable, so this proxy is not unreasonable. Ideally this resource would have been represented with two different groups of technologies: decentralized renewable sources, and centralized sources. Centralized renewable resources have some benefits, notably the increase in dispatchability (since hydrogen can be stored) over electricity. However, they face the obstacle of long-

5 The price of biomass for power generation has traditionally been low, as it usually a byproduct of the forest industry. If biomass became widely used though the price would rise. Appendix A shows the exogenous price trajectory I chose for biomass in the hydrogen and electricity production sectors, which goes from $1.22/GJ in 2005 to $20/GJ in 2050. Hydrogen from biomass was also restricted to 30% of the market share.
distance hydrogen transportation, which is more costly than transporting electricity (Keith & Leighty, 2002). Decentralized renewable resources, in contrast, require no transport but lack economies of scale and optimal resource siting.\(^6\)

- Electrolysis directly from nuclear was not included because, like renewables, nuclear technologies are listed in the electricity sector.\(^7\)

- Co-gasification of coal and biomass was omitted due to a lack of data. This could become an important technology though, particularly with CO\(_2\) capture, since it combines the low cost of coal with the GHG-reducing benefits of biomass, with relatively few plant design changes (Simbeck, 2004a).

Capital costs for all included production methods decline with cumulative production, representing savings from technical innovation.

Centralized production methods decline the most, as they also benefit from economies of scale as plant sizes progress from small to mid-size to large.

I structured the model in such a way that production methods using the same technology, for instance biomass gasification, have capital costs that

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\(^6\) NRC (2004) include both decentralized photovoltaic and wind. I believe their wind cost estimate is far too low. Renewable wind electricity costs are directly related to wind speeds (Dutton, 2000), and the average urban wind turbine would neither be optimally sited nor tall enough to take advantage of the higher wind speeds found further from the ground. The NREL's photovoltaic estimates are more accurate but solar photovoltaic electricity is far more expensive than centralized renewables put into the grid.

\(^7\) Using grid electrolysis to represent nuclear electrolysis will overestimate costs somewhat, since there are synergies that would occur with centralized nuclear hydrogen production facilities (NRC, 2004).
decline at the same rate\textsuperscript{8}. Similarly, CCS capital costs decline at the same rate throughout the entire CIMS model.

Most production data was taken directly from the U.S. National Research Council's 2004 'Hydrogen Economy' report, and checked against the Department of Energy's 2006 H2A model spreadsheets, and analyses by Lorna Greening (2005a, 2005b).\textsuperscript{9} The polygeneration coal data was obtained by combining the NRC 2004 report with data from the IPCC's 2005 'Carbon Dioxide Capture and Storage' report. Technology details can be found in Appendix A.

2.3.2 Hydrogen Infrastructure

A hydrogen economy would require an entirely new infrastructure for transporting and distributing hydrogen. The technologies are well established and are not expected to improve considerably. Improving compression and storage technologies is the main way in which innovation may decrease capital costs (NRC, 2004). But even a halving of storage capital costs would result in only a 9% decrease in total delivery costs (Ogden & Yang, 2005). An increase in scale, in contrast, generates large savings. Since

\textsuperscript{8} This was accomplished by modelling the capital cost of biomass gasification, for instance, as a service required by both biomass gasification, and biomass gasification with CCS. That way 'biomass gasification' capital costs are a function of a single cumulative production number. Appendix A includes a flowchart of the model that illustrates this structure.

\textsuperscript{9} Because the NRC's future cost estimates were meant to represent improvements that might occur only with successful R&D and significant technological breakthroughs, in my base case I set future technology costs as being halfway between the NRC's estimate of current costs and their projected future costs (i.e., I included only half their projected cost reductions).
delivery costs present a major portion of total hydrogen costs, most analysts predict production will gradually move from distributed hydrogen production towards centralized production (Mintz et al., 2002; NRC, 2004; Greening, 2005; Romm, 2003; Simbeck & Chang, 2002).

Until there is substantial demand for hydrogen, distributed production will likely dominate. These are refuelling stations that produce hydrogen onsite using natural gas or grid electricity. As demand increases, hydrogen may be shipped in compressed gas trucks, then liquid hydrogen trucks or metal hydride trucks, and eventually through pipelines (Ogden & Yang, 2005; Amos, 1998; NRC, 2004; Ringer, 2004). The optimal method depends on the amount being transported and the distance. In contrast, refuelling station costs are relatively insensitive to scale (Ogden & Yang, 2005).

Distributed generation does not entirely solve the “chicken and egg” problem—there still must be enough hydrogen vehicles on the road to support a network of fuelling stations and vice versa—but it does solve the problem of how to procure hydrogen when the market is still small. Some analysts, however, warn against large-scale investment in distributed generation that could become ‘stranded’ when centralized production takes hold or if hydrogen never becomes competitive (Romm, 2003). Others are concerned that distributed steam methane reforming cannot capture CO₂, making hydrogen vehicles fuelled in this way a transportation option with few environmental benefits (Simbeck, 2004b; Keith & Farrell, 2003).
In my model, hydrogen infrastructure is a service that encompasses transportation, distribution, storage and refuelling stations. It is used by the three centralized production methods (natural gas, coal, and biomass). Distributed steam methane reforming and grid electrolysis do not require this service, as they already include fuelling station costs.

Figure 2-2 illustrates how the lifecycle cost for infrastructure decreases in my model as more hydrogen is demanded and cumulative production grows. I followed the lead of a number of studies in choosing to make infrastructure dependent upon regional demand rather than national demand (NRC, 2004; Ogden & Yang, 2007; Simbeck & Chang, 2002). Because hydrogen infrastructure is costly, cross-country pipelines are unlikely during the transition period to hydrogen. As such, both production facility and infrastructure costs will be different for each region.

The final cost shown in Figure 2-2 represents a high-demand, pipeline scenario, with some technological improvements. It assumes large centralized plants (47M GJ) and 150km pipelines. The midsize centralized cost assumes mid-sized production plants (1M GJ) and liquid hydrogen truck transport of 150km. The initial cost is not meant to be a 'real' cost, but rather a starting

10 While capital costs are meant to correspond with the cumulative production of hydrogen, the model can only be set up so that cost declines with the cumulative demand for hydrogen infrastructure. This incorporates production from centralized sources but ignores decentralized. The curve parameters have been adjusted accordingly, but the rate of decline is nevertheless imperfect, and the Cumulative Production numbers shown in Figure 2-2 are rough estimates.
point that ensures the declining cost curve hits the midsize and final costs at the right point\textsuperscript{11}.

Figure 2-2: Cost Path for Hydrogen Infrastructure\textsuperscript{12}

Costs were derived from Ogden & Yang (2005), and NRC (2004). More technology details can be found in Appendix A.

2.3.3 CO\textsubscript{2} Capture and Storage

As mentioned in Section 1.2, CO\textsubscript{2} capture and storage (CCS) is a promising technology in which CO\textsubscript{2} is removed from a plant's emission stream, transported by pipeline, and injected deep underground into saline aquifers, depleted oil and gas reservoirs, and unmineable coal seams. The government of Canada has announced its support for CCS and passed

\textsuperscript{11} The fact that this cost is not 'real' does not skew the cost of hydrogen, because initial demand is almost entirely met with distributed generation. 'Hydrogen Infrastructure' will not gain significant market share until after mid-sized production occurs.

\textsuperscript{12} Assumes a 10% discount rate. This is the financial discount rate used to calculate the price of hydrogen, not the revealed discount rate used in technology competitions.
regulations encouraging its use by 2018 in all oil sands operations and coal
power plants beginning operation after 2012 (Government of Canada, 2008).
Nevertheless, implementing CCS will require overcoming many technical,
cost, regulatory and public acceptance hurdles.

Recognizing that CO₂ transportation and storage may not be available
in certain regions for a long time, production methods using carbon capture
and storage were given different entry dates in various regions, based on my
judgement about the time required to set up CO₂ infrastructure. Appendix A
lists these dates. Given the uncertainty around this technology, I explore the
effect of removing CCS altogether in a number of my simulations.

2.3.4 Model Competition

My aim was to simulate a transition from early distributed generation
to final large centralized production. So when hydrogen demand is very
small, the only viable option is local production at refuelling stations using
natural gas or grid electricity. But as the demand for hydrogen grows, mid-
sized centralized plants, and then larger centralized plants become viable
and dominate the market.

I employ the CIMS declining capital cost function to simulate this
transition. By making the cost of hydrogen infrastructure very high to start,
centralized production methods are excluded from the market. But as
cumulative production of hydrogen increases, the capital cost of
infrastructure goes down due to economies of scale. Once this happens, centralized production methods enter the market (at ‘mid-sized’ costs). As they gain market share, their costs go down in turn to the level of a large centralized plant, leading to prevalence in the market.

2.4 Transportation Model

CIMS contains a detailed transportation sector consisting of two models: freight and personal transportation. My project included updating or adding various hydrogen-consuming vehicles and competing technologies. In this section I summarize how the model works and list the vehicle attributes relevant to this analysis.

2.4.1 Model Structure

CIMS has an extensive model of transportation that considers both urban and intercity travel, various modes of travel (such as biking and walking), vehicle occupancy, and passenger vehicle type. Personal vehicles are classed as cars or trucks, and categorized by age (old, recent, new). In the personal transportation model, demand is measured in passenger kilometres travelled (PKT) and then converted into vehicle kilometres travelled (VKT) in the node where vehicle competition occurs. Demand for freight transportation is measured in tonnes kilometres travelled (TKT). Figure 2-3 shows the

---

13 The declining capital cost function in CIMS specifies that capital cost goes down with cumulative production of the one technology (e.g.
technology competition for new passenger vehicles. It is a nested competition, in which different types of cars compete with each other, and then with trucks, and vice versa.

Figure 2-3: New Passenger Vehicle Competition

- New Vehicle
  - Car
    - Standard Emission Vehicles
      - Low Efficiency Gasoline
      - High Efficiency Gasoline
      - Diesel
      - Gasoline Electric Hybrid
      - Gasoline Plug-in Hybrid
      - Natural Gas
    - Zero- and Near-Zero Emission Vehicles
      - Battery-Only Electric
      - E85 Ethanol
      - Hydrogen Fuel Cell
      - Hydrogen Fuel Cell Plug-in Hybrid
      - Hydrogen ICE
      - Biofuel Plug-in Hybrid Electric
      - Extended-Range Plug-in Hybrid
  - Truck
    - Standard Emission Vehicles
      - Low Efficiency Gasoline
      - High Efficiency Gasoline
      - Diesel
      - Gasoline Electric Hybrid
      - Gasoline Plug-in Hybrid
      - Natural Gas
    - Zero- and Near-Zero Emission Vehicles
      - Battery-Only Electric
      - E85 Ethanol
      - Hydrogen Fuel Cell
      - Hydrogen Fuel Cell Plug-in Hybrid
      - Hydrogen ICE
      - Biofuel Plug-in Hybrid Electric
      - Extended-Range Plug-in Hybrid
In a business-as-usual scenario, competitions occur at two levels within the truck and car nodes. In the car node, for instance, standard emission vehicles compete amongst themselves, and zero- and near-zero emission vehicles compete amongst themselves. Once each group has allocated market share between its vehicle technologies, this ensemble (e.g. ZEV and NZEV cars) then competes against the other group (standard emission vehicles). In contrast, in my policy scenarios I set a vehicle emission standard (VES), in which each group has a set total market share. Thus in the policy scenarios, NZEVs and ZEVS never have to compete against standard emission vehicles.

In CIMS, the same vehicle, e.g. a low-efficiency gasoline car, may improve its fuel efficiency over time. This is done by competing gasoline and diesel engines separately from the vehicles themselves. As carbon pricing increases the price of fossil fuels, the energy cost of low-efficiency engines increases and high-efficiency engines become more competitive and more common.

For the model to function properly, the total demand for transportation services in a base year must be allocated between the available nodes and technologies as accurately as possible. The base year for this version of CIMS has been calibrated using the 2005 Comprehensive Energy Use Database by Natural Resources Canada.
2.4.2 Vehicle Characteristics

There is a great deal of disagreement over the future 'mature' costs of many vehicle technologies. In this study I embrace this uncertainty by running scenarios using different cost assumptions. My base case scenario contains mid-range cost estimates from the literature, while other scenarios employ ‘pessimistically high’ and ‘optimistically low’ values that have been taken from high and low estimates. Table 2-2 contains information on the cars competing in CIMS.14 While gasoline cars are classed into ‘low efficiency’ (usually bigger, more powerful cars) and ‘high efficiency’ (usually smaller, economy cars), the rest of the models are meant to represent an average mid-sized, mid-efficiency car. More data can be found in Appendix B.


I chose to include vehicles based on their potential future impact on the market and discussion in the literature (see section 1.3.1). Notice that gasoline hybrid electric vehicles and plug-in hybrid electric vehicles are not

14 All truck models have corresponding costs, with an extra $12,216 added to reflect the additional cost of a larger vehicle. Fuel efficiencies are different, see Appendix A.
Table 2-2: Car Costs and Fuel Consumption

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard Emission Cars</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline, Low Efficiency</td>
<td>1990</td>
<td>$29,952</td>
<td></td>
<td></td>
<td></td>
<td>0.00256 to 0.00366</td>
</tr>
<tr>
<td>Gasoline, High Efficiency</td>
<td>1990</td>
<td>$21,217</td>
<td></td>
<td></td>
<td></td>
<td>0.00159 to 0.00227</td>
</tr>
<tr>
<td>Diesel</td>
<td>1990</td>
<td>$31,104</td>
<td></td>
<td></td>
<td></td>
<td>0.00192 to 0.00274</td>
</tr>
<tr>
<td>Gasoline Hybrid Electric</td>
<td>1990</td>
<td>$31,239</td>
<td>$29,075</td>
<td>$32,405</td>
<td>$27,460</td>
<td>0.001653</td>
</tr>
<tr>
<td>Gasoline Plug-in Hybrid17</td>
<td>2010</td>
<td>$42,840</td>
<td>$34,973</td>
<td>$38,089</td>
<td>$31,098</td>
<td>Electricity: 0.0002Gasoline: 0.00118</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>1990</td>
<td>$40,135</td>
<td></td>
<td></td>
<td></td>
<td>0.0035</td>
</tr>
<tr>
<td><strong>Zero- and Near-Zero Emission Vehicles</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery-Only Electric</td>
<td>1990</td>
<td>$65,325</td>
<td>$47,320</td>
<td>$52,867</td>
<td>$36,214</td>
<td>0.0011</td>
</tr>
<tr>
<td>E85 Ethanol</td>
<td>1990</td>
<td>$31,167</td>
<td>$34,519</td>
<td>$40,236</td>
<td>$28,802</td>
<td>Electricity: 0.0002Gasoline: 0.00072</td>
</tr>
<tr>
<td>Hydrogen Fuel Cell</td>
<td>1990</td>
<td>$171,022</td>
<td>$39,618</td>
<td>See Appendix B</td>
<td>See Appendix B</td>
<td>Electricity: 0.0002Hydrogen: 0.00076</td>
</tr>
<tr>
<td>Hydrogen Fuel Cell Plug-in Hybrid18</td>
<td>1990</td>
<td>$156,194</td>
<td>$39,618</td>
<td>See Appendix B</td>
<td>See Appendix B</td>
<td></td>
</tr>
<tr>
<td>Hydrogen ICE</td>
<td>2010</td>
<td>$45,070</td>
<td>$33,346</td>
<td>$39,265</td>
<td>$25,584</td>
<td>0.0026</td>
</tr>
<tr>
<td>Biofuel Plug-in Hybrid Electric</td>
<td>2010</td>
<td>$42,840</td>
<td>$34,973</td>
<td>$38,089</td>
<td>$31,098</td>
<td>Electricity: 0.0002Ethanol: 0.00118</td>
</tr>
<tr>
<td>Extended-Range Plug-in Hybrid19</td>
<td>2010</td>
<td>$50,422</td>
<td>$38,370</td>
<td>$42,636</td>
<td>$31,837</td>
<td>Electricity: 0.00037Gasoline: 0.00087</td>
</tr>
</tbody>
</table>

15 Listed costs are a synthesis of data, but the base case mature cost reflects a fuel cell system cost of approximately US$80/kW, the optimistically low scenario is less than US$20/kW, and the pessimistically high is US$140/kW. All of these assume some significant technological breakthroughs to achieve cost and performance targets (see section 1.3.1).

16 All cost inputs and outputs from CIMS are listed in Canadian 2005$.

17 Based on a PHEV20, specified in Simpson (2006).

18 Due to a lack of data, the hydrogen fuel cell plug-in hybrid information was generated by amalgamating various battery and fuel cell attributes. It should not be considered authoritative.

included in the ZEV and NZEV category, while extended-range gasoline plug-in hybrids and biofuel plug-ins are.

The transportation sector also includes hydrogen technologies for the following applications (see Appendix A for details):

- Transit buses
- Intercity buses
- Intercity rail
- Airplanes
- Offroad vehicles
- Road Freight
- Rail Freight
- Marine Freight

As described in Section 2.2.3, capital costs decline with cumulative production of the technology (see Figure 2-4 for example). To ensure vehicles with similar technologies have similarly declining capital costs, certain vehicles are linked so that the cumulative production between them is shared. Cars and trucks with batteries are linked in this way, as are cars and trucks with fuel cells.\textsuperscript{20} Vehicle capital and maintenance costs are uniform across Canada.

\textsuperscript{20} Fuel cell plug-in vehicles are only linked to other fuel cell vehicles rather than battery vehicles, since fuel cells account for more of the difference between initial and mature costs.
Figure 2-4: Declining Capital Cost of Hydrogen Fuel Cell Car (Endogenous Decline Only)

Certain vehicles also have an exogenous rate of decline (ERD) meant to represent technological improvements expected to occur from existing research and development rather than from increased production of these vehicles.

Intangible costs are a significant factor in vehicle technology competitions. As shown in Section 2.2.3, intangible costs are divided into fixed costs and variable costs. Fixed costs are associated with technology features or conditions that will not change, such as limited range or safety issues. Variable costs decline with market share and represent factors such as fuel availability and perceived new technology risk. High and low efficiency gasoline vehicles have widely diverging intangibles, reflecting the fact that consumers strongly prefer the horsepower and extra room.
associated with low-efficiency vehicles\textsuperscript{21}. For vehicles that are on the market, intangibles can be estimated by adjusting intangibles until CIMS market shares match actual market shares. Intangible costs for newer technologies are more difficult to estimate and rely upon a combination of judgement and recent empirical studies (Axsen, 2006a; Mau, 2005; Eyzaguirre, 2004b). Because intangible costs for newer technologies are so uncertain, I use a range of values in my scenarios to represent ‘optimistically low’ and ‘pessimistically high’ prediction of consumer acceptance.

Figure 2-5 gives an example of how intangible costs decline with market share.

\textbf{Figure 2-5: Intangible Cost Curve for Hydrogen Fuel Cell Car}

\textsuperscript{21} The negative cost assigned to low efficiency vehicles represents a benefit.
Table 2-3 lists intangible costs used in this study. Trucks have similar but lower intangible costs, to reflect consumer preferences for trucks—details can be found in Appendix B.

### Table 2-3: Intangible Costs for Cars

<table>
<thead>
<tr>
<th>Technology</th>
<th>Fixed Intangible Cost (FIC)</th>
<th>Variable Intangible Cost&lt;sup&gt;22&lt;/sup&gt; (DIC)</th>
<th>Pessimistically High</th>
<th>Optimistically Low</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard Emission Cars</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline, Low Efficiency</td>
<td>-$4,154</td>
<td>$0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline, High Efficiency</td>
<td>$7,941</td>
<td>$0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td>$1,833</td>
<td>$4,887</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline Hybrid Electric</td>
<td>$0</td>
<td>$2,395</td>
<td>FIC: $11,000</td>
<td></td>
</tr>
<tr>
<td>Gasoline Plug-in Hybrid</td>
<td>$0</td>
<td>$8,552</td>
<td>FIC: $17,157</td>
<td></td>
</tr>
<tr>
<td>Propane</td>
<td>$25,546</td>
<td>$0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td>$29,989</td>
<td>$0</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Zero- and Near-Zero Emission Cars</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery-Only Electric</td>
<td>$0</td>
<td>$8,552</td>
<td>FIC: $17,157</td>
<td></td>
</tr>
<tr>
<td>Ethanol</td>
<td>$3,054</td>
<td>$6,108</td>
<td>FIC: $17,157</td>
<td></td>
</tr>
<tr>
<td>Hydrogen Fuel Cell</td>
<td>$3,054</td>
<td>$18,325</td>
<td>FIC: $0 DIC: $6,108</td>
<td></td>
</tr>
<tr>
<td>Hydrogen Fuel Cell Plug-in Hybrid</td>
<td>$1,527</td>
<td>$18,325</td>
<td>FIC: $0 DIC: $6,108</td>
<td></td>
</tr>
<tr>
<td>Hydrogen ICE</td>
<td>$3,054</td>
<td>$6,108</td>
<td>FIC: $0</td>
<td></td>
</tr>
<tr>
<td>Biofuel Plug-in Hybrid Electric</td>
<td>$1,330</td>
<td>$11,212</td>
<td>FIC: $19,817</td>
<td></td>
</tr>
<tr>
<td>Extended Plug-in Hybrid Electric</td>
<td>$0</td>
<td>$8,552</td>
<td>FIC: $17,157</td>
<td></td>
</tr>
</tbody>
</table>

2.4.3 Other Input Assumptions

A number of other parameters also affect the market share garnered by each technology, as discussed in Section 2.2.2. I used the default values

<sup>22</sup> All variable intangible costs decline using the parameter values of $A=0.4$ and $k=65$, as empirically derived in Axsen (2006).
within CIMS, listed in Table 2-4. As discussed in section 2.2.2, $v$ is a parameter that represents variation in markets and human preferences and the cost-sensitivity of firms and households. A higher $v$ means that preferences are relatively homogenous and that the lowest-cost technology gains more market share.

Figure 2-6 shows the exogenous fuel costs. I used the default fuel price forecasts in CIMS. The price of electricity and ethanol were determined endogenously.

<table>
<thead>
<tr>
<th>Table 2-4: Other Key Model Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Revealed Discount Rate</td>
</tr>
<tr>
<td>Financial Cost of Capital$^{23}$</td>
</tr>
<tr>
<td>$v$ within emission class (e.g. standard emission cars)</td>
</tr>
<tr>
<td>$v$ within class (e.g. cars)</td>
</tr>
<tr>
<td>$v$ between classes (e.g. cars vs trucks)</td>
</tr>
</tbody>
</table>

$^{23}$ Used to calculate the final cost of transportation, but not to allocate market share in the technology competition.
2.5 Other Sectors

A number of technologies were added to the industrial, commercial and residential sectors to experiment with the possible success of hydrogen and its effect upon hydrogen fuel prices. These include:

- Steam boilers, hot water boilers, burners and direct heat
- Industrial engines
- Reheating and casting in the iron and steel industry
- Cement grinding
- Cleaning, tailings disposal, agglomeration and transport in the mining industry
- Drilling in the natural gas industry
- Residential hot water and furnaces
- Commercial hot water and heating, ventilation and air conditioning

\(^{21}\) Pictured fuel prices are from Ontario. Prices vary slightly from region to region, generally by no more than $2/GJ.
Very little data exists on future hydrogen-consuming technologies in these areas, so cost data was entered using the following assumptions.

First, the final cost of technologies combusting hydrogen will be 13% more than equivalent natural gas technology, but will initially be twice that. The 13% figure is based on the relative cost of storage for hydrogen vs natural gas (Earnst & Young, 2003). The final cost of technologies using hydrogen fuel cells will also be 13% more than equivalent natural gas technology, but will initially be ten times that.

Second, most technologies using hydrogen will use 10% less fuel than an equivalent natural gas-using technology. Industrial engines combusting hydrogen use 25% less fuel than an equivalent natural gas engine, while industrial hydrogen fuel cell engines use 55% less fuel than an equivalent natural gas engine (based on fuel efficiencies of vehicles).

Third, for industrial vehicles, e.g. mining trucks, data was taken from similar vehicles in the transportation sector.

2.6 Other Energy Carrier Production Sectors

I did not make any changes to these sectors; however, it’s worth describing some relevant features of the electricity and ethanol submodels, which create energy carriers used in the transportation sector.
2.6.1 Ethanol Production

The ethanol submodel contains production from two methods—cellulosic, and corn-based production. Corn-based production draws upon agricultural inputs, which are grown with a choice of three methods: the current method, a higher-efficiency method, and another higher-efficiency method that uses some biodiesel instead of fossil fuel-based diesel. In the CIMS model, corn-based ethanol production produces dramatically higher emissions than cellulosic—generating between ten and forty-four times the greenhouse gases. Cellulosic costs, however, are 47% higher than corn-based production, but descend with cumulative production and time to be over 25% lower than corn.

This submodel was built with data from the US Department of Energy. Using these numbers, an ethanol car has lower greenhouse gas fuel cycle emissions than a gasoline vehicle, particularly as cellulosic ethanol is adopted. As discussed in section 1.2, other studies have shown ethanol production to have much higher fuel cycle emissions (e.g. Farrell, 2006), in some cases so high as to be worse than gasoline, due to indirect land use changes (e.g. Fargione et al., 2008; Searchinger, 2008). Even these studies, however, reveal options for lower-impact production in the future.

Because there is still considerable controversy on this issue, in my analyses I consider the impacts of removing biofuel vehicles from the market. This could conceivably happen if political forces became set against this fuel,
or if new data on fuel cycle emissions were accounted for fully under a carbon tax regime.

The ClMS ethanol model also does not model the consequences of an increase in agricultural prices due to competition for land. For this reason my analyses explicitly considers the impacts of an increase in ethanol prices.

2.6.2 Electricity Production

The ClMS electricity model divides supply into base load, shoulder load, and peak load. Peak and shoulder load is limited to non-renewable energies but includes CO$_2$ capture and storage (CCS) technologies. Base load includes the following technologies (some are not available in all provinces):

- Hydro (large and small)
- Coal (single cycle, IGCC, and pulverized fluidized bed, with and without CCS)
- Natural gas (single cycle and combined cycle, with and without CCS)
- Diesel (single cycle)
- Fuel oil (heavy and light)
- Advanced nuclear CANDU reactors
- Fuel cell run on natural gas
- Biomass (with and without CCS)
- Wind
- Solar photovoltaic
- Solar parabolic trough
- Geothermal
This model is relatively complete and did not require any changes for
the purposes of this study.

2.7 Scenarios Run

My selection of scenarios was guided by themes commonly raised in
the debate around hydrogen. One of the biggest issues is how long it will take
to develop commercially viable fuel cell technology and whether it could
eventually become affordable (Kalhammer et al., 2007). To account for this
uncertainty, I organize my results based on different assumption around the
rate of capital cost decline of hydrogen vehicles.

Another major topic of discussion is the “chicken and egg” problem
(National Research Council, 2004)—how can people have hydrogen cars when
there are no fuelling stations? I get at this in two ways—by trying out
different ‘intangible costs’ for vehicles (costs which take into account fuel
availability problems)—and by exploring the dynamics of demand and supply
for hydrogen fuel.

Analysts have also debated whether hydrogen will be outcompeted by
other zero-emission vehicles (Hammerschlag & Mazza, 2005). In a number of
scenarios I vary the cost and availability of other competitors, and the price
of competing energy carriers.

Lastly, there is debate about whether we need to specifically promote
zero-emission vehicles or whether we should just stick to the goal of reducing
emissions (Kemp, 2005; Keith & Farrell, 2003; Mallory, 2007). To address this issue I employ scenarios which omit the vehicle emission standard, and others in which the criterion for the VES is changed.

2.7.1 Policies

My aim in this study was to examine the competition between hydrogen and other zero- and near-zero emission vehicles. One way in which such vehicles might gain prevalence is through carbon taxation. By putting a price on CO₂ emissions, such a policy would favour vehicles with low emissions and penalize those with high emissions. At the same time, it would ensure that the energy carriers used by ‘zero-emission vehicles’ had low fuel cycle emissions. For instance, it would reduce the chance that electric vehicles would run on dirty coal-based electricity.

Carbon taxes, or equivalent permit prices within a cap-and-trade system, seem likely in a scenario where governments are committed to reducing emissions. The National Round Table on the Environment and the Economy (2007) recently released a study indicating that a steadily rising carbon price would be needed to achieve the federal government’s 2050 emission targets. The carbon tax I applied is based on one of their scenarios, in which emission reductions of 65% below current levels are required by 2050, and there is no access to international trading of emission credits (J&C Nyboer, 2007). The increase in carbon price is rapid, but actually helps to minimize economic impacts because an earlier start on emission reductions

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reduces the need for aggressive action at a late stage. Table 2-5 shows the carbon tax schedule I applied to all policy scenarios.

Table 2-5: Carbon Tax Policy Applied to Scenarios

<table>
<thead>
<tr>
<th>Year</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
<th>2040</th>
<th>2045</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Tax ($/tonne CO\textsubscript{2}eq)</td>
<td>$0</td>
<td>$0</td>
<td>$19</td>
<td>$92</td>
<td>$183</td>
<td>$275</td>
<td>$330</td>
<td>$330</td>
<td>$330</td>
<td>$330</td>
</tr>
</tbody>
</table>

In addition to a carbon tax, I imposed a vehicle emission standard (VES) for the majority of modelled scenarios. Under this policy, auto manufacturers are required to produce an increasing number of zero- and near-zero emission vehicles. In this study, I set the minimum total market share to steadily increase to 30% of all cars on the road by 2035, and 30% of all light-duty trucks by 2035 (see Table 2-6).

Table 2-6: Vehicle Emission Standard Applied to Scenarios

<table>
<thead>
<tr>
<th>Year</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
<th>2040</th>
<th>2045</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum market share for ZEVs and NZEVs (%)</td>
<td>1%</td>
<td>2%</td>
<td>3%</td>
<td>5%</td>
<td>10%</td>
<td>20%</td>
<td>30%</td>
<td>30%</td>
<td>30%</td>
<td>30%</td>
</tr>
</tbody>
</table>

This policy has the effect of pushing the market beyond the lower-emission vehicles and behaviour stimulated by a carbon tax, and towards more profound technological change. A recent study using CIMS (Mallory, 2007) found that a VES coupled with a carbon tax actually reduces emissions more cheaply in the long run than a carbon tax alone. This can be explained by the market dynamics in the transportation sector, in which strong
economies of scale and ‘lock-in’ effects make it difficult for new technologies to break in. By creating a niche in which zero- and near-zero emission vehicles can develop, governments can foster technological advancements, infrastructure development, and consumer acceptance with the ultimate goal of developing competitive technologies (Jaccard et al., 2003; Azar & Dowlatabadi, 1999).

Because of the way CIMS structures its technology competitions, the vehicle emission standard I applied draws a clear distinction between zero- and near-zero emission vehicles, and standard emission vehicles. If a VES were actually implemented in Canada, it might make more sense to have a gradient between the policy treatment of higher emission vehicles and zero emission vehicles, as there is in California. To some degree, the CO₂ tax in this study mimics this effect by providing additional financial incentive for zero-emission vehicles over near-zero emission vehicles. Nevertheless, to provide some balance against my overly black-and-white VES policy, I included some simulations where the standard only includes pure zero-emission vehicles and excludes the NZEVs (E85 ethanol vehicles and extended-range gasoline-electric hybrids).

Similarly, the VES policy used in this study requires that 30% of vehicles on the road be zero- or near-zero emission by 2035. This particular form of VES was dictated by CIMS functionality—a more administratively feasible policy would likely follow the California mould, in which it is the
sales of vehicles rather than the total stock of vehicles that is regulated. For instance it might require that 30% of new vehicle sales be zero- or near-zero emission.

2.7.2 Simulations

The purpose of this analysis is to explore future scenarios in which hydrogen vehicles might or might not succeed. I have used a mix of fairly realistic scenarios as well as unrealistic ones, to test a wide range of possible future conditions. Given the large number of variables and their extremely uncertain nature over the course of half a century, I have chosen to assign qualitative rather than quantitative probabilities to each scenario.25 The reader may interpret results applying their own estimations of how future conditions may unfold.

Three series of simulations were run. In the first series, hydrogen vehicle capital costs decline at their 'best guess' rate, in the typical manner used in CIMS. In other words, the price of hydrogen vehicles declines primarily based on cumulative production, at rates estimated in empirical studies—specifically, using a progress ratio of 0.8. In the second series, I also

25 While no rigorous method was applied, I did assign some rough probabilities to each variable to help in ranking scenarios by probability. In most cases I assumed that there was a 50% chance of a variable being at its nominal value, with a 25% probability each for it's high and low value. When a variable's value seemed more drastic, e.g. a ban on biofuels, carbon capture, or polluting technologies in electricity production, its probability was decreased. Although the VES criteria is in fact a policy choice, it was treated as a 'state of nature' to simplify the analysis—the default VES criteria were assigned a probability of 70%. To obtain a scenario probability, I multiplied the appropriate variables' probabilities.
model capital cost declines endogenously but employ different input
assumptions about the rate and timing. In the third series, I do away with all
endogenous capital cost decline for hydrogen fuel cell vehicles, and assume
instead that costs come down exogenously in Canada as a result of aggressive
policies in another jurisdiction.

**Series 1: Scenarios with Classic Cost Decline**

In the base case for this series (scenario #1-1), all variables are set to
their 'best guess' value (my estimation of their most likely value) and
hydrogen vehicle capital costs are set to decline endogenously in the classic
manner for CIMS. In the rest of this series, the rate of decline for hydrogen
vehicle capital costs is kept the same but other variables are altered. These
simulations are grouped in the following way:

- Scenarios with the price of hydrogen fuel altered
- Scenarios with the price of electricity altered
- Scenarios with the price or availability of biofuels altered
- Scenarios with assumptions about vehicle costs altered
- Scenarios with VES criteria altered

Each scenario is assigned a qualitative probability, based on my
judgment only. The probability scale is:

Most Likely—Quite Possible—Possible—Unlikely—Very Unlikely
**Varying the Price of Hydrogen Fuel**

Table 2-7 lists a number of scenarios in which the final (2050) price of hydrogen fuel is varied. In order to take advantage of the new hydrogen model that I built, and to gain truly integrated results, I took a different approach from the typical parametric analysis in which only one variable is altered at a time. Instead, I increased or decreased the price of hydrogen indirectly, by altering other variables. Each of the scenarios were chosen not only for their depiction of the effects of higher or lower hydrogen prices, but also as interesting scenarios in and of themselves.

Note that some of these scenarios are labelled ‘hypothetical’—meaning they are not realistic but are nevertheless of interest. For instance, in several scenarios I set the initial cost of hydrogen infrastructure to its mature cost (in other words, instant pipelines), which is clearly unrealistic. The results were of interest though, because it shows us what the cost could be in the future if hydrogen gained popularity. In essence, it poses the question: if there was no ‘chicken-and-egg’ problem, would hydrogen succeed?

To increase the price of hydrogen, I tested a scenario (#1-2) in which carbon capture and storage (CCS) was removed as an option for hydrogen production. By removing CCS while imposing a carbon tax, hydrogen production remains decentralized and dominated by electrolysis, rather than switching to large-scale natural gas or coal with CCS. As a result, the price of hydrogen stays high.
Table 2-7: Scenarios with ‘Best Guess’ H₂ Vehicle Capital Cost Decline and Altered Price of Hydrogen Fuel

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Condition Explored</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>Remove CO₂ capture and storage from hydrogen production</td>
<td>High hydrogen price</td>
</tr>
<tr>
<td>1-3</td>
<td>Optimistically low hydrogen infrastructure cost</td>
<td>Low hydrogen price</td>
</tr>
<tr>
<td>1-4</td>
<td>Instant mature cost for hydrogen infrastructure and production</td>
<td>Low hydrogen price</td>
</tr>
<tr>
<td>1-5</td>
<td>Optimistically low hydrogen infrastructure cost + Instant mature cost for hydrogen infrastructure and production</td>
<td>Low hydrogen price</td>
</tr>
<tr>
<td>1-6</td>
<td>Increased hydrogen airplane demand</td>
<td>Low hydrogen price</td>
</tr>
<tr>
<td>1-7</td>
<td>Instant mature cost for all industrial hydrogen-using technologies</td>
<td>Low hydrogen price</td>
</tr>
<tr>
<td>1-8</td>
<td>Increase vehicle emission standard to 100% by 2045</td>
<td>Low hydrogen price</td>
</tr>
</tbody>
</table>

In a number of scenarios, the final price of hydrogen was brought down by increasing demand for hydrogen fuel and thus generating economies of scale in production and distribution. Scenarios #1-7 boost demands by hypothetically setting the cost of industrial hydrogen technologies to their mature level. Scenario #1-6 boosts demand by increasing the market share of hydrogen airplanes—achieved by removing the option of not flying, and halving the intangible cost of all alternative airplanes including hydrogen. Scenario #1-8 increases hydrogen demand simply by expanding the YES requirement to 100% of all vehicles by 2045.

Scenarios #1-3, #1-4, and #1-5 decrease the price of hydrogen fuel more directly, by setting the cost of hydrogen production and infrastructure to their
mature levels, or by using optimistically low costs for hydrogen infrastructure.

**Varying the Price of Electricity**

In scenarios #1-9 and #1-10, I altered the price of electricity exogenously—setting the price in each period to 30% and 100% higher, respectively, than in the business-as-usual scenarios. In contrast, scenario #1-11 changes the price of both electricity and hydrogen indirectly, by removing carbon capture and storage as an option throughout the economy. All three scenarios are listed in Table 2-8.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Condition Explored</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-9</td>
<td>Increased electricity price (exogenously)(^{26}) (\times 1.3) of BAU</td>
<td>High electricity price</td>
</tr>
<tr>
<td>1-10</td>
<td>Significantly increased electricity price (exogenously) (\times 2) of BAU</td>
<td>High electricity price</td>
</tr>
<tr>
<td>1-11</td>
<td>Remove all CO(_2) capture and storage</td>
<td>High hydrogen price; High electricity price</td>
</tr>
</tbody>
</table>

**Varying the Price and Availability of Biofuels**

Technological, economic, and political factors all have great potential to affect the future of biofuels. A number of scenarios were run to explore these factors and their effect on the zero-emission vehicle market. Table 2-9 lists these scenarios.

\(^{26}\) In scenarios 1-9 and 1-10 the electricity price is altered *exogenously*. As a result, the total emission reductions for the economy will not be accurate (since the electricity submodel is not 'hooked up' with the rest of the model).
Table 2-9: Scenarios with ‘Best Guess’ $\text{H}_2$ Vehicle Capital Cost Decline and Altered Biofuel Price and Availability

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Condition Explored</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-12</td>
<td>Remove cellulosic ethanol</td>
<td>High biofuel price</td>
</tr>
<tr>
<td>1-13</td>
<td>Gradually increase the price of ethanol and biodiesel dramatically</td>
<td>High biofuel price</td>
</tr>
<tr>
<td>1-14</td>
<td>Remove all biofuel vehicles</td>
<td>No biofuel availability</td>
</tr>
</tbody>
</table>

Scenario #1-12 explores what would happen if the ‘next generation’ of ethanol never got off the ground—if cellulosic technology never became available. This results in continuing high emissions from production and an escalating price of ethanol.

Scenario #1-13 explores what would happen if agricultural input prices increased dramatically, pushing up the price of ethanol and biodiesel—a scenario entirely conceivable in a world with increasing biofuel production combined with population growth and increased energy demand. In this scenario, I set the price of ethanol and biodiesel to gradually double exogenously from the BAU price.

Scenario #1-14 is meant to simulate a situation in which political circumstances force biofuels from the market altogether. For instance, widespread famine or high food prices could prompt governments to ban the sale of biofuel vehicles. Alternatively, if the net emission impact of biofuels was found to be negative, a carbon tax could, through economic forces,
eliminate them from the market. In this scenario, all vehicles using ethanol or biodiesel are removed from the competition.

**Varying Assumptions about the Cost of Vehicle Technologies**

Variations were made in the cost of both battery technology and hydrogen technologies, shown in Table 2-10.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Condition</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-15</td>
<td>Pessimistically high battery mature cost</td>
<td>High cost for competitor vehicles</td>
</tr>
<tr>
<td>1-16</td>
<td>Optimistically low hydrogen vehicle mature cost</td>
<td>Low H vehicle cost</td>
</tr>
<tr>
<td>1-17</td>
<td>Increase battery initial intangible cost</td>
<td>High cost for competitor vehicles</td>
</tr>
<tr>
<td>1-18</td>
<td>Optimistically low hydrogen vehicle intangible costs</td>
<td>Low H vehicle cost</td>
</tr>
</tbody>
</table>

In scenario #1-15, the mature capital cost of battery technology was increased, affecting the cost and market share of hybrids, all plug-in hybrids, and battery-only electric vehicles. A biofuel plug-in hybrid, for instance, went from requiring a $9,389 premium over an equivalent gasoline vehicle, to a $12,505 premium. Scenario #1-17, in contrast, sets the initial intangible cost of battery technology $8,605 higher than the ‘best guess’ value. This value was chosen in order to produce the same market share outcome for gasoline electric hybrid vehicles as those initially forecasted by the US Energy Information (discussed further in Chapter 3).
Scenario #1-16 and #1-18 change costs for hydrogen vehicles. In scenario #1-16, the mature capital cost of hydrogen fuel cell vehicles is set at $3,217 instead of $11,310 greater than an equivalent gas vehicle. Mature capital costs for hydrogen internal combustion engine (ICE) vehicles is altered from $7,761 greater, to the same as, an equivalent gasoline vehicle. In scenario #1-18, variable intangible costs for all hydrogen vehicles are set to the same low level as ethanol vehicles, while fixed intangibles are set to zero (the same as gasoline hybrids).

Varying the VES Criteria

The definition for ‘near-zero and zero-emission vehicles’ is somewhat arbitrary, and in Scenario #1-19 I explore how results would change if the Vehicle Emission Standard criteria were tightened to include only zero-greenhouse gas emission vehicles—in other words, if extended-range gasoline plug-in hybrids and E85 ethanol vehicles did not qualify. Scenario #1-20 adds to this a ban on biofuel vehicles, while scenario #1-21 adds to this a removal of hydrogen ICE vehicles from the VES (thus removing all vehicles that generate air pollution). In scenario #1-22, extended-range PHEVs, E85, and HICE are removed while the mature battery cost remains pessimistically high. These scenarios are listed in Table 2-11.
Table 2-11: Scenarios with ‘Best Guess’ H₂ Vehicle Capital Cost Decline and Altered VES Criteria

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Condition Explained</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-19</td>
<td>Exclude extended-range PHEV and E85 ethanol vehicles from the vehicle emission standard</td>
<td>Remove NZEV competitors</td>
</tr>
<tr>
<td>1-20</td>
<td>Exclude extended-range PHEV and E85 ethanol vehicles from the vehicle emission standard + Remove all biofuel vehicles</td>
<td>Remove NZEV and biofuel competitors</td>
</tr>
<tr>
<td>1-21</td>
<td>Exclude extended-range PHEV and E85 ethanol vehicles from the vehicle emission standard + Exclude hydrogen ICE vehicles from vehicle emission standard + Remove all biofuel vehicles</td>
<td>Remove competitors that release air pollutants</td>
</tr>
<tr>
<td>1-22</td>
<td>Exclude extended-range PHEV and E85 ethanol vehicles from the vehicle emission standard + Exclude hydrogen ICE vehicles from vehicle emission standard + Pessimistically high battery cost</td>
<td>Remove competitors; High cost for competitor vehicles</td>
</tr>
</tbody>
</table>

Series 2: ‘Delayed Entry’ and ‘Rapid Progress’ Scenarios

In this series, hydrogen fuel cell vehicle costs are modelled differently. Table 2-12 displays scenarios in which I delayed the introduction of hydrogen fuel cell vehicles until 2025. However, I assume that by this time current R&D efforts will have resulted in a reduced capital cost\(^{27}\). Assumptions for hydrogen ICE vehicles are not changed.

In a similar vein, I ran one extra simulation to test the effect of a faster rate of endogenous capital cost decline on the hydrogen fuel cell vehicle. The original base case was altered to decrease the progress ratio from

\(^{27}\) For fuel cell vehicles the initial capital cost is set to $94,334 instead of $160,413. Plug-in hydrogen fuel cell vehicles have an initial capital cost of $84,236 instead of $145,586. Because technological innovation has played its part and now economies of scale will be required to reduce costs further, the exogenous rate of capital cost decline is reduced from 2% to 0.75%/yr (the same rate as plug-in hybrid electric vehicles).
0.8 to 0.5 in hydrogen fuel cell and fuel cell plug-in hybrid vehicles. This scenario is listed in Table 2.13.

**Table 2.12: Scenarios with Delayed Entry Hydrogen Fuel Cells**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Condition Explored</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>'Delayed Entry' Base case (II)</td>
<td>Quite possible</td>
</tr>
<tr>
<td>2-2</td>
<td>Remove all biofuel vehicles</td>
<td>No biofuel availability</td>
</tr>
<tr>
<td>2-3</td>
<td>Exclude extended-range PHEV and E85 ethanol vehicles from the vehicle emission standard + Exclude hydrogen ICE vehicles from vehicle emission standard</td>
<td>Remove NZEV and HICE competitors</td>
</tr>
</tbody>
</table>

**Table 2.13: Scenario with Altered Progress Ratio for Hydrogen Fuel Cells**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Faster Fuel Cell Vehicle Progress Ratio</td>
</tr>
</tbody>
</table>

**Series 3: The ‘California Push’**

Table 2.14 considers scenarios in which hydrogen fuel cell vehicle capital costs decline exogenously to reach their mature level by 2025. You can imagine this as a ‘California Push’ situation where a foreign jurisdiction has decided to pursue fuel cell vehicles regardless of the cost, and has successfully forced the auto industry to design and mass-produce a reasonably priced hydrogen fuel cell vehicle. These simulations then test whether such a vehicle would compete well with other near-zero emission vehicles under various circumstances.
Scenario #3-2 and #3-14 examine whether these externally-developed hydrogen fuel cell vehicles could compete in the absence of a vehicle emission standard. Scenarios #3-3 to #3-7 and #3-9 correspond exactly with scenarios

Table 2-14: Scenarios with a ‘California Push’ for Fuel Cell Vehicles

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Condition Explored</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1</td>
<td>‘California Push’ Base case (III)</td>
<td>Possible</td>
</tr>
<tr>
<td>3-2</td>
<td>Remove vehicle emission standard</td>
<td>Add competitors</td>
</tr>
<tr>
<td>3-3</td>
<td>Remove all CO₂ capture and storage</td>
<td>Highest H price; High electricity price</td>
</tr>
<tr>
<td>3-4</td>
<td>Instant mature cost for hydrogen infrastructure and production</td>
<td>Low H price</td>
</tr>
<tr>
<td>3-5</td>
<td>Optimistically low hydrogen infrastructure cost + Instant mature cost for hydrogen infrastructure and production</td>
<td>Lowest H price</td>
</tr>
<tr>
<td>3-6</td>
<td>Double the price of ethanol and biodiesel</td>
<td>High biofuel price</td>
</tr>
<tr>
<td>3-7</td>
<td>Remove all biofuel vehicles</td>
<td>No biofuel available</td>
</tr>
<tr>
<td>3-8</td>
<td>Optimistically low battery mature cost</td>
<td>Change cost for competitor vehicles</td>
</tr>
<tr>
<td>3-9</td>
<td>Pessimistically high battery mature cost</td>
<td>Change cost for competitor vehicles</td>
</tr>
<tr>
<td>3-10</td>
<td>Pessimistically high hydrogen vehicle mature cost</td>
<td>Change H vehicle cost</td>
</tr>
<tr>
<td>3-11</td>
<td>Optimistically low hydrogen vehicle mature cost</td>
<td>Change H vehicle cost</td>
</tr>
<tr>
<td>3-12</td>
<td>Optimistically low hydrogen vehicle intangible cost</td>
<td>Change H vehicle cost</td>
</tr>
<tr>
<td>3-13</td>
<td>Optimistically low hydrogen vehicle mature cost + Optimistically low hydrogen vehicle intangible costs</td>
<td>Change H vehicle cost</td>
</tr>
<tr>
<td>3-14</td>
<td>Remove vehicle emission standard + Optimistically low hydrogen vehicle mature cost + Optimistically low hydrogen vehicle intangible costs</td>
<td>Change H vehicle cost; Add competitors</td>
</tr>
<tr>
<td>3-15</td>
<td>Optimistically low battery mature cost + Optimistically low hydrogen vehicle mature cost</td>
<td>Change H vehicle cost; Change cost for competitor vehicles</td>
</tr>
<tr>
<td>3-16</td>
<td>Pessimistically high battery mature cost + Pessimistically high hydrogen vehicle mature cost</td>
<td>Change H vehicle cost; Change cost for competitor vehicles</td>
</tr>
</tbody>
</table>
already described in Series 1. The remainder of Series 3 simulations explore various combinations of optimistically low and pessimistically high costs for hydrogen and battery technologies.
CHAPTER 3: RESULTS

Using the scenarios outlined in Chapter 2, this section presents the results of my model simulations. I first compare my Business As Usual forecast results with a US Energy Information Administration market forecast. I then review in detail my base case policy scenario, including the evolution of market shares, vehicle costs, fuel prices, and fuel cycle emissions. I go on to present the results of the other ‘Classic Cost Decline’ scenarios, with sections on the sensitivity of market share to fuel prices, technology costs, and policy criteria. I then consider alternative treatments of hydrogen vehicle capital cost reductions and their effect on market share. Finally, I report results for ‘California Push’ scenarios in which fuel cell costs are reduced automatically. All results are summarized in Chapter 4.

3.1 Business As Usual Forecast

A Business As Usual (BAU) forecast is a simulation in which no additional policies are applied to reduce greenhouse gas emissions or promote zero-emission vehicles, and all variables are at their ‘best guess’ value. The BAU forecast for new market share of vehicle technologies is shown in Figure 3-1. Gasoline electric hybrids do very well, rapidly gaining market share as their cost declines to maturity, stabilizing, then declining slightly as gasoline prices decrease.
This scenario can be compared with the US Energy Information Administration 2007 forecast for the US to 2030 shown in Figure 3-2 (there is no equivalent Canadian forecast). Note that there is no penetration of zero- or near-zero emission vehicles in either forecast.
However, there are large differences between the two. Given that gasoline prices used in both the US and Canada modelling were fairly close, the source of divergence must lie elsewhere.

Ethanol fuel subsidies explain in part the greater market share of ethanol in the US forecast. However, gasoline hybrid electric vehicles’ market share also varies considerably between my BAU scenario and the US EIA forecast. That difference can likely be explained by diverging assumptions about hybrid capital cost and intangible costs. To explore this issue, I ran a simulation with higher variable intangible costs (costs which decrease with market penetration). I was able to generate a scenario in which the hybrid vehicle market share matches the US EIA forecast at first, but ultimately reverts back to the more impressive share seen in my Canadian BAU run.\textsuperscript{28} To truly match the EIA forecast would require adding a fixed intangible cost to hybrid vehicles, for which there is no empirical support\textsuperscript{29}.

3.2 Series 1: Scenarios with Classic Cost Declines

The simulations in this series explore some of the more likely scenarios in which hydrogen vehicles may compete. What they have in common is the way in which costs for hydrogen technology decline. More specifically, these

\textsuperscript{28} See simulation #1-17 in Appendix C.

\textsuperscript{29} If this fixed intangible cost is applied to all battery vehicles, the effect will be similar to that seen in the 'Pessimistically high battery' scenarios. However, any penalty associated with the unfamiliarity of these vehicles, or the complications associated with electrical systems, will also likely apply to hydrogen vehicles as well. As such, adding a fixed intangible cost will not change the competition between near-zero emission vehicles except perhaps to boost the share of ethanol vehicles (which do not have electrical technologies).
vehicles have a 'progress ratio' that is extracted from the academic literature, and their cost reduction through time relies upon expanded production

3.2.1 Base Case I

In this base case scenario, all variables are set to what I consider their most likely value. Like nearly all scenarios simulated in this study, two climate policies are applied—a gradually escalating carbon tax, and a vehicle emission standard which mandates that an increasing share of the total stock of vehicles must be zero- or near-zero emission through time. Figure 3-3 shows the resulting new market share (sales) for ZEVs and NZEVs in relation to other types of light-duty vehicles. It shows clearly a peak and then fall of ZEV and NZEV sales in 2035. This is a byproduct of the way in which I

Figure 3-3: New Market Share for All Light-Duty Vehicles in Base Case I
have set up the vehicle emission standard (VES) policy—rather than dictating vehicle sales each year, it dictates the total stock of vehicles, i.e. the makeup of vehicles on the road. As a result, there is a big push for sales in 2035 (as the VES requirement ramps up from 20% to 30%). Since the VES requirement stays at 30% after that, sales then drop down to the replacement rate because, in spite of a carbon tax and induced technology advances, by the end of the study period ZEVs and NZEVs still have higher lifecycle costs than higher-emission vehicles. Nevertheless, the overall effect of the vehicle emission standard is to gradually shrink sales of all vehicles that aren't ZEV or NZEVs.

At the same time, the carbon tax acts to squeeze out some vehicles more than others. Low-efficiency gasoline vehicles suffer the most. Gasoline plug-in hybrids, in contrast, are benefited by the tax—their sales are small but growing in spite of the fact that they don't qualify for the VES. Conventional hybrids account for a large chunk of new sales, but this is caused more by a decrease in capital costs than by the carbon tax, since sales also expand in the BAU scenario (as shown in Figure 3-1).

Figure 3-4 shows the vehicle breakdown within the vehicle emission standard (VES).\textsuperscript{30} Hydrogen vehicles gain 13% of the VES new market share by 2050, but this is entirely comprised of hydrogen internal combustion engine vehicles (HICEVs). Fuel cells do not penetrate the market at all.

\textsuperscript{30} For detailed description of each of these vehicles, see Section 1.3.
Ethanol vehicles are the initial winners, given the unavailability of plug-in and hydrogen vehicles, but as these other technologies enter the market and decline in price they push out E85 ethanol vehicles. Biofuel plug-in vehicles are the biggest winner, with 46% of VES new market share in 2050.

Figure 3-4: VES New Market Share in Base Case I

Figure 3-5 helps to explain these results. The cost per vehicle kilometre (VKT) represents all costs, including capital, operating and maintenance, intangible, and fuel costs. The costs shown here are for Ontario, but all regions will be nearly the same with some variation caused by differing fuel prices. The figure clearly shows how the cost of hydrogen fuel cell and fuel cell plug-in vehicles decline, but not rapidly enough or far enough for them to compete.
Figure 3-6 gives a close-up of the more competitive technologies. Most reach their mature cost within a few decades of introduction. You can see that battery size strongly impacts final cost—biofuel plug-ins (with their smaller batteries) are less costly than extended-range gasoline plug-ins, which in turn far out-compete battery-only electric vehicles. You can also see that for some cars, costs drop initially but rebound slightly afterwards. This
is caused by change in fuel prices. As carbon taxes increase, the price of gasoline gradually doubles, affecting the operating costs for any vehicles using the fuel, including E85 ethanol vehicles and extended-range gasoline plug-in hybrids. In contrast, the cost per GJ of hydrogen descends below gasoline in some regions, but remains above those of electricity and ethanol. While ethanol is the cheapest fuel on a per-GJ basis by 2050, electric-drive vehicles consume less energy and are therefore cheaper to run.

**Hydrogen Prices**

The average Canadian price of hydrogen in this scenario increases from $45/GJ initially to $51/GJ in 2030, ultimately declining to $35/GJ by 2050. The extent of the decline varies considerably region by region, as provinces with higher populations and fuel demand are able to bring down the cost with economies of scale. But the general pattern of transformation holds. Initially, distributed natural gas is the most affordable small-scale production method, but carbon taxes shift the market towards more expensive distributed electrolysis using grid electricity. Once sufficient economies of scale are reached, there is a transition towards cheaper centralized production. Biomass with carbon capture is the first centralized method to be adopted, as it has additional revenue-generation benefits (selling carbon credits from sequestration). Then natural gas and coal, both with carbon capture, also come onboard. Nationwide, 51% of the total production is in centralized facilities by 2050.
Fuel Cycle Emissions

As discussed in Chapter 1, zero-emission vehicles can generate emissions indirectly through the production and transport of their energy carriers (fuels). 'Fuel cycle' emissions account for both the direct emissions caused by fuel use, and the indirect emissions. Figure 3-7 shows the Canadian average fuel cycle emission intensity of a number of vehicles.

Initially, all of the vehicles have positive emissions. Most have emission intensities lower than a conventional gasoline hybrid—a useful benchmark since hybrids are cheaper than ZEVs and NZEVs, and have greater consumer acceptance. HICEVs and E85 ethanol vehicles, however, actually have emissions that are higher than a hybrid. Why, then, should they be promoted with a VES? Because over time, their emissions dip lower, while a hybrid’s stays the same. Specifically, the direct emissions from each GJ of gasoline combusted cannot change, while the indirect emissions from ethanol, hydrogen, and electricity can go down over time, even while vehicle fuel consumption stays the same.

Using this same logic, all zero-emission vehicles gradually decline towards zero as their fuel production processes become lower-emission, while near-zero emission vehicles such as E85 ethanol and extended-range gasoline plug-ins have emission paths that gradually flatten out and remain positive, because of the gasoline portion of their fuel input.
In this base case, carbon taxes force the electricity and hydrogen production facilities to reduce emissions by adopting renewable energy and using CO₂ capture and storage technologies. In fact, both of these energy transformation activities eventually become net reducers of CO₂, because they couple the use of biomass with CO₂ capture and storage. In the ethanol sector, ethanol production goes from being corn-based to being cellulosic-based, which is less emission intensive. Processing facilities and tractors

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51 Emissions from vehicle manufacture are not included. Electricity, ethanol, and hydrogen include emissions from production, taken directly from the CIMS simulation. Gasoline emissions include the CIMS coefficient for transportation gasoline combustion plus 30%. This is based on a U.S. estimate of upstream emissions from gasoline, published by Delucchi (1991). If emission reduction from the oil and gas industry becomes popular globally, this upstream component may decrease significantly from 30%.
switch to using biofuels instead of coal and gasoline, respectively. By 2050 the life cycle emissions for a GJ of ethanol decrease by 96%.

Because electricity and hydrogen have net negative emissions by 2045, their use actually reduces emissions. As a result, vehicles consuming electricity or hydrogen reduce emissions (thus HICEVs have the lowest emissions in 2050). If biomass with CCS were removed from the hydrogen and electricity production sectors, then hydrogen vehicles would approach but not quite reach zero, as would biofuel plug-ins, while battery-only electric vehicles would reach zero.

These emission intensities will vary greatly between provinces for any vehicles using electricity. On average, electricity production in 2005 generates 70% of the emissions per GJ that gasoline production and use do, because of the share of electricity produced with coal. But in Quebec, where the electricity system is dominated by hydro power, a ‘green’ electric car is truly green. In contrast, an electric car fuelled in Alberta, with its coal-reliant system, is actually worse in 2005 than a gasoline car. As carbon capture and other emission reduction measures are implemented, however, these regional differences decline.

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32 This is on a per GJ basis. However, electric cars use far less energy than do gasoline vehicles, so on a VKT basis the electricity emissions are not as high.
Other Transportation Demand

Because in my study only light duty vehicles have a vehicle emission standard, other hydrogen vehicles (i.e., hydrogen buses, trains, planes, offroad vehicles, and freight), do not find success. The exception is marine freight, where hydrogen gains 15% of new market share in 2050. The success of this particular sector, however, may be an artefact of modelling inputs—while I updated fuel consumption for hydrogen marine freight technologies based on similar technologies (see Appendix B), I did not update all other vehicle classes, which have assigned to them a broad speculative future efficiency for all alternative technologies. As such, adoption of hydrogen technologies for non-light-duty transportation may be underestimated, and the success of marine freight hydrogen may only seem successful in comparison. On the other hand, marine freight has been identified elsewhere as a good candidate for employing hydrogen technology (Farrell et al., 2003).

Industrial Demand

Transportation accounts for the vast majority of hydrogen demand—96% in year 2050 of the base case. Among non-transport sector applications, mining is the largest, particularly in British Columbia and the Atlantic region, where it makes up 14% of demand. However, this demand comes primarily from specialized mining vehicles and transport. Hydrogen also has some minor success in the iron and steel industry.
3.2.2 Scenarios with Altered Hydrogen Price

In these simulations, all vehicle attributes remain at their ‘best guess’ value, and other factors are changed that result in hydrogen fuel price changes. Figure 3-8 summarizes the relationship between hydrogen price and hydrogen vehicle market penetration within the vehicle emission standard (VES) in 2050. These scenarios represent a fair range of possible hydrogen prices.

There appears to be a linear relationship in which new market share within the VES increases by about 12% for every $10/GJ decrease in the price of hydrogen. Note however that this only shows the hydrogen price in 2050—what the hydrogen price is in earlier time periods will also affect results, since this could impact the decline of vehicle capital costs.

Figure 3-8: Hydrogen Price vs Hydrogen New Market Share in 2050
In the base case, the average price of hydrogen in Canada descends to $35/GJ by 2050. In another scenario we assume, hypothetically, that hydrogen production centralizes and achieves its mature cost instantly, allowing us to see that economies of scale alone can bring the price of hydrogen down to $22/GJ—the same price as electricity (this also raises the VES new market share for hydrogen marine freight to 38% and airplanes to 57% by 2050). However, if infrastructure costs are lower than expected, the lowest hydrogen fuel cost is $19/GJ.

Increasing hydrogen demand will also push down the cost of production and transportation, thus increasing hydrogen vehicle market penetration. If hydrogen demand from airplanes is increased, the cost of hydrogen descends to $29/GJ in 2050. Boosting demand from the non-transportation sectors causes hydrogen in 2050 to descend to $28/GJ. If the vehicle emission standard is raised to 100% of all cars and trucks by 2045, hydrogen costs go down to $26/GJ. Total hydrogen demand increases for these scenarios can be found in Appendix C.

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33 Hydrogen airplanes do well because of a lack of other zero-emission options. Biofuel airplanes are not zero-emission because their fuel must include 50% turbo fuel to prevent problems at low temperatures (Daggett et al., 2007). See Appendix B.

31 The carbon tax regime that I used in the base case results in a 'no fly' rate of 88% in 2050. In other words, 88% of would-be flights are foregone in favour of travelling by land or not travelling at all. I believe this is unrealistically high. To promote hydrogen airplanes in this scenario without biasing against other alternatives, I initially increased the intangible cost of not flying so that the 'no fly' rate is zero. Hydrogen airplanes do well but not until 2050. To speed up the process so that we could see the resulting price impacts I also reduced the intangible costs of all alternative airplanes. As a result, 48% of airplane sales in 2050 are hydrogen.

35 Done by setting hydrogen-using technologies in all other sectors to their mature cost.
Lastly, I created a high-priced hydrogen scenario by removing CO\textsubscript{2} capture and storage technologies from the hydrogen production sector, which suppresses centralization. In this scenario, carbon taxes shift hydrogen production towards more expensive electrolysis while preventing more economical options involving coal and natural gas. As a result, the price of hydrogen actually rises (with carbon taxes) from $45/GJ in 2005 to $48/GJ in 2050.

### 3.2.3 Scenarios with Altered Electricity Price

Two simulations were run in which the price of electricity was altered exogenously, to test the effect of electricity price on hydrogen vehicle penetration. Figure 3-9 shows a 2.5% increase in VES penetration for every $10/GJ increase in electricity price, although one should be cautious in extrapolating from just three data points.

This lack of sensitivity is not surprising, since electric-drive vehicles are more fuel efficient than hydrogen ICE vehicles. As a result, their lifecycle costs rise only slightly in spite of electricity price increases, and thus have little effect on the competition between zero- and near-zero emission vehicles.

I also tested the effect of removing all CO\textsubscript{2} capture and storage technologies (not shown in figure), which impacts both the electricity and the hydrogen price. As a result, market penetration of hydrogen vehicles
decreased from 13% to 6% within the VES. Hydrogen production is more reliant on carbon capture because the main CO₂-free alternative production process, electrolysis, is very expensive. In contrast, electricity generation from renewable sources is in many cases competitive with fossil fuel combustion with CO₂ capture. As a result, in this scenario carbon taxes affect the price of hydrogen more than the price of electricity. At the same time, hydrogen vehicle penetration is more sensitive to the price of hydrogen than to the price of electricity.

3.2.4 Scenarios with Altered Ethanol Price and Availability

Three simulations were done to explore the impact of biofuel assumptions on hydrogen vehicle penetration, shown in Figure 3-10. In the

36 CO₂ capture is more costly with electricity because the CO₂ is diffuse in the flu stream, whereas in the production of hydrogen, CO₂ is produced as a nearly pure byproduct.
first simulation, cellulosic (low-emission) ethanol technology was removed, causing the final price of ethanol to increase substantially because of farming and production emissions. Comparing this with the 'base case' scenario, the impact on hydrogen vehicle penetration within the VES appears to be 11% for every $10/GJ increase—almost as great as the impact of hydrogen price changes. However, the impact declines with the next two scenarios. In the second simulation, the price of ethanol and biodiesel is gradually but dramatically increased.\textsuperscript{37} Compared with the first scenario, there is now only

Figure 3-10: Ethanol Price vs Hydrogen VES New Market Share in 2050

\textsuperscript{37} There are no biodiesel cars and light trucks but biodiesel is used in public transit, freight and offroad vehicles.
a 1.3% increase in penetration with every $10/GJ increase. In the third scenario, all vehicles using ethanol or biodiesel are removed under the assumption that biofuels are banned or otherwise severely restricted by governments. In this last scenario we can see that hydrogen penetration within the VES levels out at 40% of new market share, primarily because extended-range gasoline plug-in vehicles remain as a less costly alternative to hydrogen.

3.2.5 Scenarios with Alternative Assumptions about Vehicle Technology Costs

The mature capital cost of alternative vehicle technologies is an unknown variable that will affect the success of hydrogen. Two simulations experiment with the cost of battery technologies. One of these simulations increases the initial intangible cost of battery vehicles to a point where the gasoline hybrid market share matches the BAU scenario generated by the US Energy Information Administration in the short term. The result: hydrogen vehicle market penetration within the VES in 2050 is 14%—only 1% greater than in the base case.

The other scenario uses pessimistically high assumptions about the mature cost of batteries, which affects hybrids, all plug-ins, and battery-only electric vehicles. A biofuel plug-in hybrid, for instance, costs $3,116 more than it does in the base case. In this case, the VES new market share for hydrogen vehicles in 2050 is boosted from 13% to 28%.
Perhaps the factor with the strongest impact on penetration is the mature capital cost of hydrogen vehicles themselves. In an optimistically low scenario, hydrogen ICE capital costs decline to the same level as a conventional vehicle. Not surprisingly, HICEVs in this scenario gain 68% of new market share within the vehicle emission standard.

Lastly, I experimented with changing the intangible costs of hydrogen vehicles and found that in an optimistically low scenario—one in which the fixed intangible costs were as low as ethanol cars and the variable intangible costs were the same as plug-ins—hydrogen vehicle VES penetration in 2050 increased dramatically to 46%.

3.2.6 Scenarios with Different VES Criteria

Four simulations were run which experimented with the effect of excluding certain technologies from the vehicle emission standard. Removing the two NZEVs (E85 ethanol and extended range gasoline plug-ins) from the VES primarily results in a greater prevalence of biofuel plug-ins, but also boosts the hydrogen ICE vehicle market share to 24% in 2050. However if, in addition, biofuel vehicles are removed from CIMS, hydrogen ICE vehicles dominate the VES market with a 77% share in 2050, with hydrogen fuel cell plug-in vehicles finally gaining market share—but only 3%.

A third scenario applied the most stringent criteria of all: excluding vehicles with any type of air pollution from combustion, which includes HICE vehicles and biofuels. Biofuel vehicles were removed from the model while
HICEVs were only removed from the VES portfolio. The effect is, for the first time, real success for fuel cell technologies. Hydrogen fuel cell plug-ins gain 71% of new market share, with the balance being taken by battery-only electric vehicles (its only remaining non-hydrogen competitor).

Hydrogen fuel cells cannot gain prominence by the removal of hydrogen ICE vehicles. I ran a scenario in which hydrogen ICE, E85, and extended-range gasoline plug-in vehicles were removed from the VES, and even when battery costs were assumed to be pessimistically high, hydrogen fuel cell plug-ins only gained 1% of the VES market.

3.2.7 Summary of ‘Classic Cost Decline’ Scenarios

Figure 3-11 summarizes results for all Series 1 scenarios. The scenarios are group by their probability, with the most likely at the top and the least likely and ‘hypothetical’ listed at the bottom. Probability is partly a function of how many conditions are varied from their ‘best guess’ value, and partly on how extreme the altered condition is.

The bar graphs show the new market share allocation within the vehicle emission standard (VES) in 2050. You can see the overall penetration of hydrogen vehicles by focusing on the solid coloured segments (black, grey, and white) on the left side of each bar (grey and white are often missing since fuel cell technologies do so poorly).
In nearly all of these scenarios, hydrogen vehicles use internal combustion engines rather than fuel cells. The high initial capital cost of fuel cells ensures that they do not have the opportunity to gain market share and thereby decline in cost. Any attempt to force fuel cell development by removing hydrogen internal combustion vehicles (HICEVs) from the VES simply results in a near-elimination of any kind of hydrogen vehicle.

In the base case, hydrogen vehicles gain a respectable 13% of new market share in 2050 but are not in the lead. The most likely reason for them to gain the lead would be a dramatic rise in the price of biofuels, shown in the second-to-last row of the ‘Quite Possible’ group. Also conceivable is a surge generated by optimistically low intangible costs for hydrogen vehicles (shown in the second-to-last row of the ‘Possible’ group)—if my assumptions are flawed, or manufacturers succeed in minimizing any feature drawbacks, or perhaps if there is a groundswell of public support. Similarly, if HICEV capital costs are lower than expected (on par with conventional vehicle costs) then VES penetration surges to 68% (shown in the third-to-last row of the ‘Possible’ group). Only in the unlikely circumstance that its main competitors, biofuel vehicles and extended-range PHEVs, are removed from the market, do hydrogen vehicles gain an overwhelming market share of 81% within the vehicle emission standard. If HICEVs are also excluded then the VES share of hydrogen vehicles declines to 72% but is dominated by hydrogen fuel cell
plug-in hybrids, which have certain initial cost and efficiency advantages over pure fuel cell vehicles.
The market penetration of hydrogen vehicles is somewhat sensitive to the price of hydrogen fuel and biofuels, and fairly insensitive to the price of electricity.

The fuel cycle emissions for all ZEVs decline to zero or negative within several decades. While there could be some justification for policies favouring ZEVs over NZEVs, there is little reason for singling out hydrogen vehicles for promotion.

More detailed results, including final hydrogen prices, hydrogen demand, and total emissions, can be found in Appendix C.

I should note that there appears to be one advantage to promoting hydrogen vehicles, which deserves greater attention perhaps in another study. In my simulations, when light-duty hydrogen vehicles do well, they reduce the price of hydrogen, making hydrogen technologies in other applications with fewer emission reduction options—such as air travel—more viable. For instance, in my simulations I found that reducing the price of hydrogen in 2050 from $35 to $22/GJ reduced total national emissions in 2050 19% below the base case. However my confidence in these results is low, since (a) my data inputs for hydrogen technologies outside of the light-duty vehicle sector are poor, and (b) there may be other emission-reduction options apart from hydrogen that have not been included in these sectors.

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38 See Appendix C, simulations 1-1 and 1-4.
Recommendations on future research in this area are given in the conclusion.

3.3 Series 2: ‘Delayed Entry’ and ‘Rapid Progress’ Scenarios

I ran a number of scenarios in which hydrogen vehicle costs are modelled differently. In the first of these, the ‘Delayed Entry’ base case (II) scenario, rather than including fuel cell vehicles in the market immediately and allowing cumulative production to reduce capital costs, I instead delayed the introduction until 2025 but assumed that by this time current research and development efforts will have resulted in a reduced capital cost. The results, however, are identical to the ‘Classic Cost Decline’ base case (I). I also tried two more simulations with additional conditions which could promote hydrogen, and these too had nearly identical results to the equivalent ‘Classic Cost Decline’ scenarios. The problem is the same as in the base case from Series 1—the cumulative production of fuel cell technologies is not sufficient for the cost to come down, because it is outcompeted from the beginning by cheaper technologies like biofuel plug-ins and extended-range gasoline plug-ins.

39 For fuel cell vehicles the initial capital cost is set to $94,334 instead of $160,413. Plug-in hydrogen fuel cell vehicles have an initial capital cost of $84,236 instead of $145,586. Because technological innovation has played its part and now economies of scale will be required to reduce costs further, the exogenous rate of capital cost decline is reduced from 2% to 0.75%/yr (the same rate as PHEVs).
Lastly, I tried altering the declining capital cost in another way. Keeping the original start date and initial capital cost, I instead altered the progress ratio of hydrogen fuel cell vehicles from 0.8 to 0.5 (a very rapid rate) in order to spur more rapid capital cost reductions. Again, this made almost no difference to the simulation results because fuel cell technology gains little cumulative production. In sum, the failure of hydrogen fuel cells to compete against other vehicles within the VES seems to be a fairly robust result, standing up against changes in the way capital cost decline was modelled.

3.4 Series 3: The ‘California Push’ Scenarios

What if capital costs for fuel cell technology did decline, regardless of poor uptake in Canada—perhaps because of a single-minded push for these technologies in another jurisdiction like California? My Series 3 scenarios attempt to capture such a situation by setting capital costs for hydrogen fuel cell technologies to decline exogenously (i.e. at a set rate through time) and reach their mature level by 2025.

In the ‘California Push’ base case, all variables are set to their ‘best guess’ value except for the rate of decline for fuel cell capital costs, as described above. Figure 3-12 shows the evolution of vehicle emission standard (VES) vehicle sales for the ‘California Push’ base case. In 2020 hydrogen fuel cell and fuel cell plug-in vehicles begin to appear in the market, very gradually growing to 20% of VES new market share. Fuel cell plug-ins do better at first because of their lower initial cost, but fuel cell-only vehicles
later gain the lead, as they don’t have the extra expense of a large battery. Fuel cells do not take away market share from HICEVs because HICEVs have also benefited from the reduced hydrogen fuel prices caused by greater overall hydrogen success.

Figure 3-12: VES New Market Shares in ‘California Push’ Base Case

While all three hydrogen vehicles types together gain a total of 32% of VES new market share by 2050, biofuel plug-in vehicles still gain more new market share. A hydrogen fuel cell car at maturity costs a few hundred dollars less than a biofuel plug-in hybrid, but its high ‘intangible’ costs—the safety and availability issues with hydrogen, the unfamiliarity of an entirely new technology—combined with a higher fuel price, make it less attractive to consumers.

However, the success of hydrogen vehicles changes considerably when conditions are changed. In Series 1, hydrogen vehicles were never serious contenders in the competition, and only drastic conditions could change this.
But in this series, smaller changes are more influential because fuel cell vehicles are 'in the game'. In particular, because both hydrogen technologies and battery technologies reach their mature costs in this series, the levels at which these are set are extremely important. Figure 3-13 presents VES market share results in 2050 for all 'California Push' scenarios. The scenarios are group by their probability, with the most likely at the top and the least likely and ‘hypothetical’ (unrealistic but of interest) listed at the bottom. You can see the overall penetration of hydrogen vehicles by focusing on the solid coloured segments (black, grey, and white) on the left side of each bar.

The success of hydrogen is extremely sensitive to final vehicle capital costs. If you look at the scenarios listed under ‘Unlikely’, you can see that optimistically low final costs for hydrogen vehicles lift the VES new market share for hydrogen up to 78%, while pessimistically high costs drive it down to 4%. Likewise, pessimistically high battery costs can bring VES new market share up to 48%, while optimistically low battery costs can shrink it to 13% and remove fuel cell-only vehicles altogether. If both batteries and hydrogen vehicles have low costs (shown in Figure 3-13 under the ‘Very Unlikely’ heading), the net effect is an increase in the hydrogen vehicle share to 53% of the VES. But if both have high costs, the net effect is a reduction to only 7% of VES new market share. This is because there is more uncertainty in the cost of fuel cell technology than there is in battery technology—the cost
difference between a high estimate and a ‘best guess’ estimate is almost twice as large for a fuel cell car as it is for a biofuel plug-in hybrid.
Altering intangible costs also has a marked effect on penetration. The difference between ‘best guess’ and ‘optimistic’ intangible costs for hydrogen fuel cell cars is about $15,000. Optimistically low hydrogen vehicle intangible costs bring the lifecycle cost of hydrogen cars lower than biofuel plug-in hybrids, and raise hydrogen vehicle VES penetration to 70% (shown in the
last row of the ‘Unlikely’ section). Both hydrogen fuel cell and ICE vehicles compete successfully against biofuel plug-ins when hydrogen vehicle intangible costs are lowered. The difference is caused directly—from lower intangible costs—and indirectly—from lower hydrogen costs as hydrogen demand increases. When optimistically low intangible costs are coupled with optimistically low hydrogen mature vehicle costs, hydrogen vehicles dominate, gaining 95% of VES new market share in 2050. However, there is little evidence to suggest intangible costs will be this low for such a disruptive technology.

Figure 3-13 also shows that immediately low hydrogen infrastructure and production costs (shown in the ‘Hypothetical’ section) can bring the hydrogen vehicle VES penetration up to 48%, while removing biofuels can cause it to jump to 66% (shown in the ‘Possible’ category). An increase in hydrogen prices, caused by a ban on CO₂ capture and storage (shown in the first row of the ‘Very Unlikely’ section), shrinks hydrogen penetration within the VES down to 18%.

Two additional scenarios were run in which the vehicle emission standard was removed (not shown in Figure 3-13). Without a VES, hydrogen vehicles gain zero new market share in 2050. If, however, there are optimistically low hydrogen mature vehicle costs and intangible costs,

40 See Appendix C for a figure comparing lifecycle costs with ‘best guess’ vs ‘optimistic’ intangible hydrogen costs
hydrogen vehicles account for 86% of all new vehicles in 2050—including conventional vehicles.

3.4.1 Summary of ‘California Push’ Scenarios

To summarize, the success of hydrogen vehicles in these scenarios is highly subject to factors which are highly uncertain and perhaps quite unlikely. If hydrogen technologies have the opportunity to develop because of government forcing, as they do in these ‘California Push’ scenarios, they may succeed dramatically. But some low probability conditions are also required. In scenarios where hydrogen vehicles succeed, fuel cells can be found in a large number of hydrogen vehicles but hydrogen internal combustion engines may also play a significant role.
CHAPTER 4: CONCLUSIONS

In this chapter I summarize my research and results, drawing out potential insights about the market for zero- and near-zero emission vehicles. I offer a number of recommendations for policymakers, and conclude with suggestions for future research.

4.1 Summary

The objective of this research was to explore the conditions under which hydrogen might succeed in a carbon-constrained world as a significant zero-emission energy carrier in the transportation sector. Using CIMS, a hybrid energy-economy model, I ran numerous simulations of Canada in which different assumptions were made about capital costs, technology performance, infrastructure, fuel prices, and other conditions over a 45-year timeframe. All scenarios include a carbon tax that rose to $330/\text{tCO}_2e$ by 2035, and a vehicle emission standard that mandated a minimum market share for zero- and near-zero emission vehicles, which escalated to 30% by 2035.

CIMS captures the dynamics of a market as it evolves by employing several functions. First, it allows individual technologies’ capital costs to decline with cumulative production, reflecting empirical observations about
innovation and scale effects. Second, it allows consumer acceptance to expand as market penetration increases, a phenomenon known as the ‘neighbour effect’. Lastly, as a technology-specific model it competes technologies whose inputs, e.g. fuel costs, change over time in response to markets and policies such as carbon taxes. Prior to this research project, CIMS was unable to apply any these functions to hydrogen, because it lacked an endogenous (internally-determined) price for hydrogen. As a part of my project, I built a hydrogen production model for CIMS which created an endogenous price for hydrogen. This model simulated a transition from distributed hydrogen facilities and processes to centralized production, taking into account economies of scale in production, transportation and fuelling infrastructure. Most production methods involve the use of fossil fuels, with the option to capture and store CO₂ emissions. My study also included updating and adding to the model’s database of hydrogen-consuming technologies throughout the economy. My primary research output is the market penetration rate for various types of vehicles by 2050, but I also report on the final cost of hydrogen, hydrogen demand, and greenhouse gas emissions.

In my base case—in which all variables are set to their ‘best guess’ value—hydrogen vehicles acquire a 13% share of new zero- and near-zero emission vehicles by 2050. Nearly all of these hydrogen-fuelled vehicles have internal combustion engines rather than fuel cells. The biggest winner in the market, gaining 46% of new market share within the vehicle emission
standard (VES), is the biofuel plug-in hybrid, which has relatively low capital and fuel costs. Extended-range gasoline plug-in hybrids also do well at 24% of VES sales, but suffer from expensive larger batteries and the high cost of gasoline as carbon taxes rise. Battery-only electric vehicles scarcely survive with only 4%—the cost of the batteries is too high. Ethanol vehicles are a reasonably priced option right from the beginning, but because their biofuel is mixed with fossil fuel-derived gasoline, their initial market dominance declines to only 13% by 2050.

The inability of fuel cells to independently gain market share seems to be a robust conclusion—I ran a number of simulations with different treatment of its capital cost decline and found nearly identical results. The mediocre success of hydrogen ICE vehicles is also fairly robust to changes in the price of hydrogen, electricity, and biofuels. Its market penetration, however, would be greatly enhanced by the removal of biofuels from the market (jumping to 40% of the VES new market share), unexpectedly high consumer acceptance (45%), or capital costs as low as conventional vehicles (68%).

I also ran a series of simulations in which fuel cell capital costs came down automatically and reached their mature level by 2025. This was meant to represent cases where another jurisdiction successfully forced investment and economies of scale for this technology. In the base case for these simulations, hydrogen vehicles gain 32% of the VES new market share, with
the majority of this going to vehicles with fuel cells. A doubling of the price of biofuels expands this to 64%. Optimistically low intangible costs (consumer acceptance) boost it to 70%, or low mature capital costs to 78%. However, hydrogen vehicle sales can just as easily become very small when there are high hydrogen vehicle capital costs (to 4%), optimistically low battery costs (14%), or high hydrogen costs (18%).

The average price of hydrogen in the first base case is $45/GJ in 2005, rises to 51$ by 2030, and then drops to 35$ by 2050 as production becomes centralized and low-emission. Although in theory centralization could bring the cost down to $22/GJ, or 19$ if I’ve overestimated infrastructure costs, in even scenarios in which hydrogen vehicles are enormously successful, the average price of hydrogen fuel in Canada only declines to $24/GJ by 2050. Saskatchewan, Manitoba and the Atlantic have smaller vehicle markets which demand less hydrogen, and thus have considerably higher delivered hydrogen prices.

In this study I’ve tried to address uncertainty by exploring a variety of scenarios for the future. In any given scenario, between one and three variables were altered from their nominal or ‘base case’ value. While I was careful to try out multiple simulations with those variables I felt were particularly uncertain or important—such as the availability of biofuels, or the capital cost decline for fuel cells—there is nevertheless no guarantee that
my ‘base case’ values are correct, and therefore that my suite of scenarios is centered on the right set of nominal values.

4.2 Insights

While care should be taken in drawing conclusions from any modelling exercise, this study suggests some insights that will be of interest to policymakers, citizens and investors. First, under an escalating carbon tax or cap-and-trade system, in which renewable resources and CO₂ capture and storage technologies are available, the complete fuel cycle emissions of all zero-emission vehicles could reach zero within several decades. Consequently, there may be little justification for promoting one type of zero-emission vehicle over another. As such, other factors such as cost, ease of market transition, and air quality may be important. The one advantage of promoting hydrogen vehicles is that it leads to lower hydrogen prices, which may facilitate the adoption of hydrogen in sectors with fewer emission-reduction options, such as air travel.

Second, even with a zero-emission vehicle emission standard in place, hydrogen fuel cell vehicles seem unlikely to succeed against competition from other near-zero and zero-emission vehicles. The high initial capital cost of hydrogen fuel cell vehicles may prevent them from gaining enough new market share to achieve economies of scale and the investment in innovation needed to make them affordable. Even in the circumstance where all non-
hydrogen competitors are removed, hydrogen fuel cell plug-in hybrids have a better chance of succeeding initially than pure fuel cell vehicles.

Third, hydrogen internal combustion engine vehicles, in contrast, could carve out a share of new vehicle sales, though they may find less success than biofuel plug-in hybrids and extended-range hybrids. This is because, although their final capital cost is lower, they pay more for fuel and are less efficient than their electric-drive counterparts.

Fourth, hydrogen’s most likely chance at success is if biofuels fail to remain viable—either due to problems with their fuel cycle emissions, or due to their impact on agricultural prices. Hydrogen vehicles would then be only competing against battery-only electric vehicles, whose battery costs are likely to remain prohibitive, and extended-range gasoline plug-in hybrids, which are not zero-emission. They would of course dominate the market if their costs became as low as conventional vehicles, or if consumer acceptance was exceptionally high.

Fifth, if government policy in a key jurisdiction with market influence, such as California, succeeded in garnering investment and economies of scale for fuel cell vehicles, then these vehicles could gain about a fifth of the new vehicle sales in Canada. Again, the additional removal of biofuels would cause hydrogen, including fuel cells, to dominate the market. Consumer acceptance is a major obstacle—if intangible costs were lower than expected and matched those of other less disruptive technologies, hydrogen vehicles
could beat out all other zero- and near-zero-emission options. However, governments considering such an approach should be warned—there is a significant risk of failure. High vehicle capital costs, low battery costs, or high hydrogen fuel costs could block any success for hydrogen vehicles.

Sixth, if all hydrogen production were to become large-scale and centralized, the price of hydrogen could match that of electricity. However, in even the most optimistically low scenario for hydrogen vehicle penetration, this does not occur by 2050.

Lastly, declining hydrogen prices stimulate a strong positive feedback loop that extends beyond light duty vehicles. Lower hydrogen fuel prices create a cascading effect, causing greater adoption of hydrogen technologies in airplanes, shipping, and large trucks, which in turn stimulates demand, centralizes hydrogen production, and lowers the fuel price still more. The overall effect could be a reduction in emissions, although this conclusion would require further study.

In sum, the prospects for hydrogen vehicles are not as good as many have hoped. Hydrogen internal combustion engine vehicles may have a role to play; hydrogen fuel cell vehicles may have a much lower likelihood, unless governments intervene aggressively. A substantial success for hydrogen vehicles depends probably on the failure of biofuels and the exclusion of near-zero emission vehicles. Fuel cells could dominate the market but probably only if they were actively pushed towards commercialization and encountered
other favourable circumstances such as high biofuel prices, wide consumer acceptance, or extra-low capital costs.

4.3 Policy Recommendations

This study did not examine the advantages or disadvantages of different types of policy. The policy assumptions were chosen to represent a future in which emission reductions are aggressively pursued via carbon pricing and zero- and near-zero emission vehicle regulations. The vehicle emission standard creates a market niche within which such vehicles compete on equal ground. The value of such an approach over a carbon pricing-only approach has been studied elsewhere (Mallory, 2007).

Economic analyses generally warn governments against ‘picking technology winners’ (Loschel, 2002). However, given the economies of scale and path-dependency of transportation technologies, such actions could conceivably be justified if the targeted technology proved ‘optimal’ in the long run (Azar & Dowlatabadi, 1999). This study shows the potential risks in favouring one zero-emission vehicle technology over another when the environmental outcome is nearly identical in the long run. Investing heavily in hydrogen fuel cell technology could be a waste of resources given the factors that appear to favour other near-zero and zero-emission technologies.

My recommendation for governments trying to meet GHG-reduction targets, is to adopt policies, such as a vehicle emission standard, which
promote the outcome, rather than the technology. In other words, aim for zero- and near-zero emission vehicles rather than fuel cells specifically. Moreover, if governments wish to invest directly in zero-emission technologies, it might be wise to support the development of cellulosic ethanol, battery technology, or hydrogen fuelling infrastructure (for hydrogen ICE vehicles).

4.4 Suggestions for Further Research

4.4.1 Quantitative Treatment of Probability

My research has been an exploratory analysis in which I altered a large number of variables in various combinations, in order to discover which might most influence the market penetration of hydrogen vehicles. I assigned only qualitative probabilities to each scenario to help the reader interpret the results. However, a more quantitative approach is possible. By assigning probabilities, however tentative, to each variable’s state (e.g. there is a 30% chance that the price of biofuel will double), one could calculate an expected probability for the market success of hydrogen (Morgan & Henrion, 1990). The researcher could then explore how this value changes depending on the probabilities assigned to each scenario. This would be a valuable, but computationally more extended, analysis. My study has laid the groundwork by, (a) preparing the CIMS model, and (b) helping to identify which variables are most important—biofuel availability, exogenous fuel cell capital cost decline, hydrogen vehicle final cost, and consumer acceptance.
4.4.2 Positive Feedback Effects Outside of Light-Duty Vehicles

Farrell et al. (2003) do an analysis of what factors would make a sector ideal for the introduction of hydrogen, and conclude that the marine freight could be a good niche in which immature technologies could be tested and perfected prior to commercialization in other applications. In my research I've taken the opposite approach, targeting the light-duty vehicle sector first and then observing how the resulting impact on hydrogen prices in turn encourages adoption in other sectors. These spillover effects from vehicle policies appeared to be significant for both marine freight and airplanes, causing a decrease in emissions that contrasted with the light-duty vehicle sector, where hydrogen held no environmental advantage over other zero-emission vehicles. While my confidence in this finding is low, I do feel that a more thorough analysis of hydrogen in other sectors would be worthwhile. Specifically, one could explore whether policies targeting freight or airplanes could reduce emissions while increasing the success of hydrogen in the light duty vehicle sector.

4.4.3 Intangible Costs for Disruptive Technologies

This study found that consumer acceptance (the intangible cost) was a major factor in the success or failure of various vehicles. At the same time, the input values for hydrogen vehicles were highly uncertain. Eyzaguirre (2004b) found only limited success in empirically estimating this parameter for hydrogen vehicles using discrete choice methodology, due to consumer
unfamiliarity with the technology and disruptive nature of hydrogen vehicles and their fuelling requirements. Nevertheless such information would have been very valuable to my study, and I suggest further research in the area. Ideally such a study would also break down what intangible factors are most important—for instance, is fuelling station scarcity the determining factor for purchase, or is it safety?

### 4.4.4 Air Pollution

This study only considered greenhouse gas emissions. However, the concept of zero-emission vehicles originally developed in the context of air pollution and this is likely to remain a major factor in the urban areas where ZEV adoption will occur first. My results show success for both hydrogen ICE vehicles and biofuel vehicles, both of which emit some local air pollutants. I recommend future studies incorporate the impact of these emissions—perhaps through an air pollution cap-and-trade system or pricing scheme.

### 4.4.5 Biofuel Trends

In my study, the success of biofuel plug-in vehicles (and resulting failure of hydrogen vehicles) was based on certain assumptions about the development and cost of ethanol as a low-emission energy carrier. However, a number of recent studies (Fargione et al., 2008; Searchinger, 2008) have suggested that the use of ethanol for transportation may have negligible or even positive net emission impacts. The global increase in land and food
prices has also brought up the issue of competition with food crops, which threatens the political viability of biofuels. Further research could incorporate more of these factors into CIMS, perhaps by developing a land use model that accounted for both the emissions impacts of indirect land use changes, and the price impact of agricultural land scarcity.

4.4.6 Biomass with CO₂ Capture and Storage

In my model of hydrogen supply, I included a technology for biomass gasification with CO₂ capture and storage, and added a similar technology within the electricity sector. These technologies would actually be net reducers of greenhouse gas emissions. I arbitrarily capped them at 30% of new market share to prevent them from dominating entirely, but recommend a more thorough investigation of this technology’s potential. Would it be limited by biomass availability, and how would it impact the price of biofuels? Could energy become a cheap by-product of the ‘sequestration’ industry? What policies might regulate this industry? I envision such a study being done outside of CIMS, perhaps informing future CIMS simulations on the cost and availability of these technologies.


APPENDICES
APPENDIX A
Table A-1: Cost Information for Hydrogen Production and Delivery

<table>
<thead>
<tr>
<th>Technology</th>
<th>Initial Capital Cost ($)</th>
<th>Mature Cap. Cost ($)</th>
<th>Life-time</th>
<th>Operating &amp; Maintenance Cost ($/yr)</th>
<th>Output 41 (GJ/yr)</th>
<th>Exog. DCC (%/yr)</th>
<th>DCC Production Input</th>
<th>Progress Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass Gasification</td>
<td>160,708,587</td>
<td>36,962,975</td>
<td>20</td>
<td>2,238,511</td>
<td>946,868</td>
<td>2000</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Biomass Gasification with CCS 42</td>
<td>160,708,587</td>
<td>36,962,975</td>
<td>20</td>
<td>2,259,047</td>
<td>946,868</td>
<td>2000</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Coal Gasf Poly</td>
<td>99,423,211</td>
<td>25,502,054</td>
<td>20</td>
<td>1,394,633</td>
<td>946,868</td>
<td>2000</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Coal Gasf Poly with CCS</td>
<td>99,423,211</td>
<td>25,502,054</td>
<td>20</td>
<td>1,407,271</td>
<td>946,868</td>
<td>2000</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Natural Gas Steam Reforming</td>
<td>38,911,035</td>
<td>10,358,118</td>
<td>20</td>
<td>743,775</td>
<td>946,868</td>
<td>2000</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Natural Gas Steam Reforming with CCS</td>
<td>38,911,035</td>
<td>10,358,118</td>
<td>20</td>
<td>823,465</td>
<td>946,868</td>
<td>2000</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Distributed Grid Electrolysis</td>
<td>3,373,552</td>
<td>2,065,289</td>
<td>7</td>
<td>61,760</td>
<td>18,937</td>
<td>3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distributed Natural Gas Steam Reforming</td>
<td>2,457,115</td>
<td>1,866,179</td>
<td>7</td>
<td>56,049</td>
<td>18,937</td>
<td>1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCS Capital Cost 43</td>
<td>1</td>
<td>0</td>
<td>30</td>
<td>1</td>
<td></td>
<td>1</td>
<td>1,350,000,000</td>
<td>0.7</td>
</tr>
<tr>
<td>H2 Infrastructure</td>
<td>10,995,201,539</td>
<td>3,599,828,984</td>
<td>20</td>
<td>114,338,441</td>
<td>47,343,420</td>
<td>600,000</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>H2 Infrastructure, Optimistically low</td>
<td>10,995,201,539</td>
<td>2,592,000,000</td>
<td>20</td>
<td>114,338,441</td>
<td>47,343,420</td>
<td>600,000</td>
<td>0.8</td>
<td></td>
</tr>
</tbody>
</table>

41 The plant output listed is not important except as it is used to calculate the life cycle cost. These life cycle costs go down with cumulative production, and correspond with costs for mid-sized plants (1M GJ) and eventually centralized plants (47M GJ) depending on the cumulative production of hydrogen in the region.

42 Biomass technologies have been limited to 30% of new market share.

43 To calculate the capital cost of CCS that is added to each production method: [CCS Capital Cost (initially 1$)] x [method’s Output] x [method’s CCS Services Required in table A-2]. For biomass for instance, [1$] x [946,868] x [3.69] = $3,493,943
Table A-2: Additional Information for Hydrogen Production and Delivery

<table>
<thead>
<tr>
<th>Technology</th>
<th>Intro Year</th>
<th>CO₂ Emissions (tonnes/yr)</th>
<th>Fuel Use (GJ/GJ Output)</th>
<th>CCS Services Required</th>
<th>Infrastructure Services Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass Gasification</td>
<td>1995</td>
<td>0</td>
<td>Biomass: 2.098</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Biomass Gasification with CCS</td>
<td>See Table A-3</td>
<td>-0.18193125</td>
<td>Biomass: 2.098</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Coal Gasf Poly</td>
<td>1995</td>
<td>0.081167929</td>
<td>Coal: 1.586</td>
<td>-0.034</td>
<td>1</td>
</tr>
<tr>
<td>Coal Gasf Poly with CCS</td>
<td>See Table A-3</td>
<td>0.009566629</td>
<td>Coal: 1.586</td>
<td>0.013</td>
<td>1</td>
</tr>
<tr>
<td>Natural Gas Steam Reforming</td>
<td>1995</td>
<td>0.055859235</td>
<td>NG: 1.277</td>
<td>0.079</td>
<td>1</td>
</tr>
<tr>
<td>Natural Gas Steam Reforming with CCS</td>
<td>See Table A-3</td>
<td>0.007618647</td>
<td>NG: 1.330</td>
<td>0.107</td>
<td>1</td>
</tr>
<tr>
<td>Distributed Grid Electrolysis</td>
<td>1995</td>
<td>0</td>
<td>1.531</td>
<td>4.529</td>
<td>1</td>
</tr>
<tr>
<td>Distributed Natural Gas Steam Reforming</td>
<td>1995</td>
<td>0.077</td>
<td>NG: 1.543</td>
<td>0.059</td>
<td>1</td>
</tr>
</tbody>
</table>

Table A-3: Introduction Year for CO₂ Capture and Storage in Hydrogen Production Sector

<table>
<thead>
<tr>
<th>Region</th>
<th>Intro Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>2015</td>
</tr>
<tr>
<td>AB</td>
<td>2005</td>
</tr>
<tr>
<td>SK</td>
<td>2005</td>
</tr>
<tr>
<td>MB</td>
<td>2010</td>
</tr>
<tr>
<td>ON</td>
<td>2020</td>
</tr>
<tr>
<td>QC</td>
<td>2025</td>
</tr>
<tr>
<td>AT</td>
<td>2025</td>
</tr>
</tbody>
</table>
Figure A-1: Hydrogen Production Model Flowchart

- Steam Methane Reforming
  - Natural Gas
  - Natural Gas with CCS
- Coal Polygeneration
  - Coal Polygeneration
  - Coal Polygen with CCS
- Biomass Gasification
  - Biomass Gasification
  - Biomass Gasification with CCS
- Distributed Grid Electrolysis
  - Distributed Grid Electrolysis
- Distributed Steam Methane Reforming
  - Distributed Steam Methane Reforming

Services:
- SMR
  - Coal Gasification Polygeneration
  - Biomass Gasification
- H2 Delivery
- CO2 Capture Cost
## Table A-4: Price of Biomass Used in Hydrogen and Electricity Production Sectors

<table>
<thead>
<tr>
<th>Year</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
<th>2035</th>
<th>2040</th>
<th>2045</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood Price (S/GJ)</td>
<td>1.22</td>
<td>1.22</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>7</td>
<td>14</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>
APPENDIX B
Table B-1: Mature Capital Costs for Hydrogen Fuel Cell Plug-in Hybrid Cars

<table>
<thead>
<tr>
<th>Mature Capital Cost</th>
<th>Pessimistically High Fuel Cell</th>
<th>Base Case</th>
<th>Optimistically Low Fuel Cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pessimistically High Battery Cost</td>
<td>$35,097</td>
<td>$32,125</td>
<td>$29,153</td>
</tr>
<tr>
<td>Base Case</td>
<td>$31,982</td>
<td>$29,009</td>
<td>$26,037</td>
</tr>
<tr>
<td>Optimistically Low Battery Cost</td>
<td>$28,106</td>
<td>$25,134</td>
<td>$22,162</td>
</tr>
</tbody>
</table>

Table B-2: Additional Technology Information on Cars

<table>
<thead>
<tr>
<th>Technology</th>
<th>Exogenous DCC (%/yr)</th>
<th>DCC Progress Ratio</th>
<th>DCC Production Input</th>
<th>Direct CO₂e Emissions (kg/VKT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Emissions Cars</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline, Low Efficiency</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline, High Efficiency</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline Hybrid Electric</td>
<td>0.3%</td>
<td>0.9</td>
<td>1,470,588</td>
<td>0.1126</td>
</tr>
<tr>
<td>Gasoline Plug-in Hybrid</td>
<td>0.8%</td>
<td>0.7</td>
<td>1,470,588,235</td>
<td>0.0803</td>
</tr>
<tr>
<td>Natural Gas</td>
<td></td>
<td></td>
<td></td>
<td>0.1742</td>
</tr>
<tr>
<td>Near-Zero Emission Cars</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery-Only Electric</td>
<td>1.0%</td>
<td>0.7</td>
<td>1,470,588,235</td>
<td>0.0490</td>
</tr>
<tr>
<td>E85 Ethanol</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen Fuel Cell</td>
<td>2.0%</td>
<td>0.8</td>
<td>1,470,588</td>
<td></td>
</tr>
<tr>
<td>Hydrogen Fuel Cell Plug-in</td>
<td>2.0%</td>
<td>0.8</td>
<td>1,470,588</td>
<td></td>
</tr>
<tr>
<td>Hybrid</td>
<td>2.0%</td>
<td>0.8</td>
<td>1,470,588,235</td>
<td></td>
</tr>
<tr>
<td>Hydrogen ICE</td>
<td>2.0%</td>
<td>0.8</td>
<td>1,470,588,235</td>
<td></td>
</tr>
<tr>
<td>Biofuel Plug-in Hybrid</td>
<td>0.8%</td>
<td>0.7</td>
<td>1,470,588,235</td>
<td></td>
</tr>
<tr>
<td>Extended-Range</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plug-in Hybrid</td>
<td>0.8%</td>
<td>0.7</td>
<td>1,470,588,235</td>
<td>0.0592</td>
</tr>
</tbody>
</table>

44 All cars are assumed to: supply 19,168 vehicle-kilometres-travelled per year; have $1069 in yearly operating and maintenance cost; have a 16-yr lifespan.
Table B-3: Additional Information on Trucks

<table>
<thead>
<tr>
<th>Technology</th>
<th>Fuel Use (GJ/VKT)</th>
<th>Direct CO₂e Emissions (kg/VKT)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard Emissions Vehicles</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasoline, Low Efficiency</td>
<td>0.003904 to 0.005578</td>
<td>0.2658 to 0.3798</td>
</tr>
<tr>
<td>Gasoline, High Efficiency</td>
<td>0.002062 to 0.002946</td>
<td>0.0140 to 0.2006</td>
</tr>
<tr>
<td>Diesel</td>
<td>0.002548 to 0.003640</td>
<td>0.1798 to 0.2569</td>
</tr>
<tr>
<td>Gasoline Hybrid Electric</td>
<td>0.002294</td>
<td>0.1562</td>
</tr>
<tr>
<td>Gasoline Plug-in Hybrid</td>
<td>Gasoline: 0.001638</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electricity: 0.00085</td>
<td>0.1115</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>0.0046</td>
<td>0.2290</td>
</tr>
<tr>
<td><strong>Near-Zero Emissions Vehicles</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery-Only Electric</td>
<td>0.0015</td>
<td></td>
</tr>
<tr>
<td>E85 Ethanol</td>
<td>Ethanol: 0.00361</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gasoline: 0.00096</td>
<td>0.0654</td>
</tr>
<tr>
<td>Hydrogen Fuel Cell</td>
<td>0.0031</td>
<td></td>
</tr>
<tr>
<td>Hydrogen Fuel Cell Plug-in Hybrid</td>
<td>Electricity: 0.00085</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydrogen: 0.000783</td>
<td></td>
</tr>
<tr>
<td>Hydrogen ICE</td>
<td>0.0035</td>
<td></td>
</tr>
<tr>
<td>Biofuel Plug-in Hybrid Electric</td>
<td>Ethanol: 0.001638</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Electricity: 0.00085</td>
<td></td>
</tr>
<tr>
<td>Extended-Range Plug-in Hybrid</td>
<td>Electricity: 0.00158</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gasoline: 0.001202</td>
<td>0.0819</td>
</tr>
</tbody>
</table>

45 Trucks have identical information to cars except: Capital costs are $12,216 more; yearly VKT is 20,897; higher fuel use and emissions (see table).
Table B-4: Freight Vehicle Information

<table>
<thead>
<tr>
<th>Technology</th>
<th>Intro. Year</th>
<th>Initial Capital Cost</th>
<th>Cap. Cost at Maturity</th>
<th>Operating and Maintenance Cost</th>
<th>Output (TKT/yr)</th>
<th>Fuel Use (GJ/TKT)</th>
<th>Upfront DIC 47</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marine freight biodiesel</td>
<td>1990</td>
<td>92,848,369</td>
<td>88,205,950</td>
<td>3,665,067</td>
<td>802,139,037</td>
<td>0.0004014</td>
<td>48,867,562</td>
</tr>
<tr>
<td>Marine freight heavy fuel</td>
<td>1990</td>
<td>88,724,776</td>
<td>3,665,067</td>
<td>802,139,037</td>
<td>0.0005352</td>
<td>48,867,562</td>
<td></td>
</tr>
<tr>
<td>Marine freight heavy fuel high Eff</td>
<td>1990</td>
<td>92,848,369</td>
<td>3,665,067</td>
<td>802,139,037</td>
<td>0.0004014</td>
<td>36,650,672</td>
<td></td>
</tr>
<tr>
<td>Marine freight hydrogen</td>
<td>2020</td>
<td>132,019,275</td>
<td>112,216,384</td>
<td>3,665,067</td>
<td>802,139,037</td>
<td>0.0002920</td>
<td>12,216,891</td>
</tr>
<tr>
<td>Road freight light-med diesel Med Eff</td>
<td>1990</td>
<td>119,726</td>
<td>166,110</td>
<td>0.0055524</td>
<td></td>
<td>152,711</td>
<td></td>
</tr>
<tr>
<td>Road freight light-med diesel high Eff</td>
<td>1990</td>
<td>141,716</td>
<td>120,459</td>
<td>0.0027762</td>
<td></td>
<td>152,711</td>
<td></td>
</tr>
<tr>
<td>Road freight light-med hybrid biodiesel</td>
<td>1990</td>
<td>141,716</td>
<td>120,459</td>
<td>0.0027762</td>
<td></td>
<td>152,711</td>
<td></td>
</tr>
<tr>
<td>Road freight light-med hydrogen</td>
<td>2020</td>
<td>244,338</td>
<td>166,110</td>
<td>0.0027762</td>
<td></td>
<td>183,253</td>
<td></td>
</tr>
<tr>
<td>Road freight heavy diesel Med Eff</td>
<td>1990</td>
<td>195,470</td>
<td>166,110</td>
<td>0.0055524</td>
<td></td>
<td>152,711</td>
<td></td>
</tr>
<tr>
<td>Road freight heavy diesel high Eff</td>
<td>1990</td>
<td>212,574</td>
<td>166,110</td>
<td>0.0027762</td>
<td></td>
<td>152,711</td>
<td></td>
</tr>
<tr>
<td>Road freight heavy hybrid biodiesel</td>
<td>1990</td>
<td>212,574</td>
<td>166,110</td>
<td>0.0027762</td>
<td></td>
<td>152,711</td>
<td></td>
</tr>
<tr>
<td>Road freight heavy hydrogen</td>
<td>2020</td>
<td>305,422</td>
<td>599,771</td>
<td>0.0016113</td>
<td></td>
<td>244,338</td>
<td></td>
</tr>
<tr>
<td>Rail freight Regular</td>
<td>1990</td>
<td>665,436</td>
<td>79,733,868</td>
<td>0.0002200</td>
<td></td>
<td>366,507</td>
<td></td>
</tr>
<tr>
<td>Rail freight electric</td>
<td>1990</td>
<td>2,218,119</td>
<td>79,733,868</td>
<td>0.0001100</td>
<td></td>
<td>366,507</td>
<td></td>
</tr>
<tr>
<td>Rail freight hybrid Biodiesel</td>
<td>1990</td>
<td>2,218,119</td>
<td>79,733,868</td>
<td>0.0001100</td>
<td></td>
<td>122,169</td>
<td></td>
</tr>
<tr>
<td>Rail freight hydrogen</td>
<td>2020</td>
<td>3,881,709</td>
<td>79,733,868</td>
<td>0.0001100</td>
<td></td>
<td>366,507</td>
<td></td>
</tr>
</tbody>
</table>

46 All cost inputs and outputs from CIMS are listed in Canadian 2005$.

47 All variable intangible costs decline (DIC) using the parameter values of A=0.4 and k=65, as empirically derived in Axsen (2006). None of these vehicles have a fixed intangible cost.
Table B-5: Passenger Vehicle Information

<table>
<thead>
<tr>
<th>Technology</th>
<th>Intro. Year</th>
<th>Initial Capital Cost(^{48})</th>
<th>Initial Cost at Maturity</th>
<th>Output (VKT/yr)(^{49})</th>
<th>Fuel Use (GJ/VKT)</th>
<th>Intangible Cost(^{50})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air intercity standard</td>
<td>1990</td>
<td>154,159,298</td>
<td>264,186,398</td>
<td>0.0015152</td>
<td></td>
<td>Upfront DIC: 122,168,906</td>
</tr>
<tr>
<td>Air intercity high Eff</td>
<td>1990</td>
<td>194,085,448</td>
<td>155,268,358</td>
<td>264,186,398</td>
<td>0.0012173</td>
<td>Upfront DIC: 97,735,125</td>
</tr>
<tr>
<td>Air intercity biodiesel</td>
<td>2015</td>
<td>194,085,448</td>
<td>155,268,358</td>
<td>264,186,398</td>
<td>Biodiesel: 0.000609</td>
<td>Upfront DIC: 97,735,125</td>
</tr>
<tr>
<td>Air intercity hydrogen</td>
<td>2025</td>
<td>244,337,812</td>
<td>158,819,578</td>
<td>264,186,398</td>
<td>0.0014700</td>
<td>Upfront DIC: 122,168,906</td>
</tr>
<tr>
<td>No Fly</td>
<td>2005</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Annual FIC: 0.215/VKT/yr</td>
</tr>
<tr>
<td>Bus intercity diesel</td>
<td>1990</td>
<td>305,422</td>
<td>3,000,000</td>
<td>0.0007557</td>
<td></td>
<td>Upfront DIC: 366,507</td>
</tr>
<tr>
<td>Bus intercity diesel high Eff</td>
<td>1990</td>
<td>488,676</td>
<td>317,639</td>
<td>3,000,000</td>
<td>0.0002519</td>
<td>Upfront DIC: 366,507</td>
</tr>
<tr>
<td>Bus intercity hybrid biodiesel</td>
<td>1990</td>
<td>488,676</td>
<td>317,639</td>
<td>3,000,000</td>
<td>0.0002519</td>
<td>Upfront DIC: 366,507</td>
</tr>
<tr>
<td>Rail intercity diesel</td>
<td>1990</td>
<td>665,436</td>
<td>630,000,000</td>
<td>0.0017101</td>
<td></td>
<td>Upfront DIC: 122,169</td>
</tr>
<tr>
<td>Rail intercity diesel high Eff</td>
<td>1990</td>
<td>2,218,119</td>
<td>887,248</td>
<td>630,000,000</td>
<td>0.0008550</td>
<td>Upfront DIC: 366,507</td>
</tr>
<tr>
<td>Rail intercity electric</td>
<td>1990</td>
<td>2,218,119</td>
<td>887,248</td>
<td>630,000,000</td>
<td>0.0008550</td>
<td>Upfront DIC: 122,169</td>
</tr>
<tr>
<td>Rail intercity hybrid biodiesel</td>
<td>1990</td>
<td>2,218,119</td>
<td>887,248</td>
<td>630,000,000</td>
<td>0.0008550</td>
<td>Upfront DIC: 366,507</td>
</tr>
<tr>
<td>Rail intercity hydrogen</td>
<td>2020</td>
<td>3,881,709</td>
<td>1,746,769</td>
<td>630,000,000</td>
<td>0.0008550</td>
<td>Upfront DIC: 366,507</td>
</tr>
<tr>
<td>Bus urban diesel</td>
<td>1990</td>
<td>305,422</td>
<td>870,750</td>
<td>0.0022000</td>
<td></td>
<td>Upfront FIC: 610,845</td>
</tr>
<tr>
<td>Bus urban electric</td>
<td>1990</td>
<td>610,845</td>
<td>870,750</td>
<td>0.0009000</td>
<td></td>
<td>Upfront DIC: 183,253</td>
</tr>
<tr>
<td>Bus urban electric hybrid</td>
<td>1990</td>
<td>427,591</td>
<td>277,934</td>
<td>870,750</td>
<td>0.0011000</td>
<td>Upfront DIC: 183,254</td>
</tr>
<tr>
<td>Bus urban hybrid biodiesel</td>
<td>1950</td>
<td>427,591</td>
<td>277,934</td>
<td>870,750</td>
<td>0.0011000</td>
<td>Upfront DIC: 183,254</td>
</tr>
<tr>
<td>Bus urban hydrogen</td>
<td>1950</td>
<td>691,222</td>
<td>385,771</td>
<td>870,750</td>
<td>0.0011890</td>
<td>Upfront DIC: 183,255</td>
</tr>
</tbody>
</table>

---

\(^{48}\) All cost inputs and outputs from CIMS are listed in Canadian 2005$.  

\(^{49}\) Vehicle lifetimes are: Airplanes 15 yrs (except 'No Fly' is 5); Intercity Bus 16 yrs; Intercity Rail 25 yrs; Urban Bus 16 yrs.  

\(^{50}\) All variable intangible costs (DIC) decline using the parameter values of A=0.4 and k=65, as empirically derived in Axsen (2006).
APPENDIX C
Figure C-1: Fuel Prices in Ontario for Base Case I

Figure C-2: Hydrogen Production Total Stock in Ontario, by Technology, in Base Case I
Life cycle costs for hydrogen vehicles are lower in Ontario, because economies of scale lead to lower hydrogen fuel prices. In this figure you can see that even in the ‘California Push’ base case, fuel cell vehicles have the same LCC as biofuel plug-ins by 2050.
<table>
<thead>
<tr>
<th>Scenario</th>
<th>New Market Share of H Cars &amp; Trucks within VES in 2050</th>
<th>HICE vehicles + All H vehicles in 2050</th>
<th>Hydrogen Price in 2050</th>
<th>Transportation Hydrogen Demand in 2050</th>
<th>Total Hydrogen Demand in 2050</th>
<th>GHG emissions (Mt) in 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-0 Base Case BAL</td>
<td>N/A</td>
<td>N/A</td>
<td>38</td>
<td>4,739,470</td>
<td>6,073,209</td>
<td>1,217</td>
</tr>
<tr>
<td>1-1 Base case I</td>
<td>13%</td>
<td>99%</td>
<td>35</td>
<td>63,620,852</td>
<td>66,522,516</td>
<td>133</td>
</tr>
<tr>
<td>1-2 Remove CO₂ capture and storage from hydrogen production</td>
<td>7%</td>
<td>100%</td>
<td>48</td>
<td>36,675,053</td>
<td>38,689,688</td>
<td>136</td>
</tr>
<tr>
<td>1-3 Optimistically low hydrogen infrastructure cost</td>
<td>27%</td>
<td>99%</td>
<td>19</td>
<td>546,220,704</td>
<td>781,474,432</td>
<td>99</td>
</tr>
<tr>
<td>1-4 Instant mature cost for hydrogen infrastructure and production</td>
<td>24%</td>
<td>99%</td>
<td>22</td>
<td>483,487,608</td>
<td>607,827,456</td>
<td>108</td>
</tr>
<tr>
<td>1-5 Optimistically low hydrogen infrastructure cost + Instant mature cost for hydrogen infrastructure and production</td>
<td>27%</td>
<td>99%</td>
<td>19</td>
<td>441,828,448</td>
<td>544,903,040</td>
<td>112</td>
</tr>
<tr>
<td>1-6 Increased hydrogen airplane demand</td>
<td>18%</td>
<td>99%</td>
<td>29</td>
<td>217,698,900</td>
<td>224,018,384</td>
<td>138</td>
</tr>
<tr>
<td>1-7 Instant mature cost for all industrial hydrogen-using technologies</td>
<td>18%</td>
<td>99%</td>
<td>28</td>
<td>144,761,792</td>
<td>190,351,600</td>
<td>126</td>
</tr>
<tr>
<td>1-8 Increase vehicle emission standard to 100% by 2045</td>
<td>20%</td>
<td>98%</td>
<td>26</td>
<td>278,190,124</td>
<td>285,247,712</td>
<td>75</td>
</tr>
</tbody>
</table>

Note that in these scenarios, total greenhouse gas emissions are often a function of the scenario inputs, rather than the success of hydrogen.
Table C-2: Results for ‘Classic Cost Decline’ Scenarios (Series 1), Cont’d

<table>
<thead>
<tr>
<th>Scenario</th>
<th>New Market Share of H Cars &amp; Trucks within VES in 2050</th>
<th>HICE vehicles + All H vehicles in 2050</th>
<th>Hydrogen Price in 2050</th>
<th>Transportation Hydrogen Demand in 2050</th>
<th>Total Hydrogen Demand in 2050</th>
<th>GHG emissions (Mt) in 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-9</td>
<td>Increased electricity price (exogenously) ---x1.3 of BAU</td>
<td>14% 100% 34</td>
<td>60,474,484</td>
<td>64,402,384</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>1-10</td>
<td>Significantly increased electricity price (exogenously) ---x2 of BAU</td>
<td>18% 100% 29</td>
<td>96,800,580</td>
<td>111,334,384</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>1-11</td>
<td>Remove all CO₂ capture and storage</td>
<td>6% 98% 52</td>
<td>31,840,469</td>
<td>33,812,616</td>
<td>568</td>
<td></td>
</tr>
<tr>
<td>1-12</td>
<td>Remove cellulosic ethanol</td>
<td>28% 99% 26</td>
<td>222,252,232</td>
<td>236,730,208</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>1-13</td>
<td>Double the agricultural crop input price for ethanol, double the biodiesel price</td>
<td>35% 99% 25</td>
<td>318,447,712</td>
<td>335,297,888</td>
<td>177</td>
<td></td>
</tr>
<tr>
<td>1-14</td>
<td>Remove all biofuel vehicles</td>
<td>40% 99% 26</td>
<td>368,135,592</td>
<td>376,210,848</td>
<td>176</td>
<td></td>
</tr>
<tr>
<td>1-15</td>
<td>Pessimistically high battery mature cost</td>
<td>28% 99% 26</td>
<td>160,926,826</td>
<td>165,073,248</td>
<td>131</td>
<td></td>
</tr>
<tr>
<td>1-16</td>
<td>Optimistically low hydrogen vehicle mature cost</td>
<td>68% 100% 26</td>
<td>381,272,456</td>
<td>389,356,480</td>
<td>118</td>
<td></td>
</tr>
<tr>
<td>1-17</td>
<td>Increase battery initial intangible cost</td>
<td>14% 100% 34</td>
<td>69,169,966</td>
<td>72,161,792</td>
<td>135</td>
<td></td>
</tr>
<tr>
<td>1-18</td>
<td>Optimistically low hydrogen vehicle intangible costs</td>
<td>46% 96% 26</td>
<td>301,093,928</td>
<td>308,487,424</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td>1-19</td>
<td>Exclude extended-range PHEV and E85 ethanol vehicles from the vehicle emission standard</td>
<td>24% 100% 28</td>
<td>159,847,648</td>
<td>164,007,728</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>1-20</td>
<td>Exclude extended-range PHEV and E85 ethanol vehicles from the vehicle emission standard + Remove all biofuel vehicles</td>
<td>81% 96% 24</td>
<td>619,543,468</td>
<td>638,298,688</td>
<td>160</td>
<td></td>
</tr>
<tr>
<td>1-21</td>
<td>Exclude extended-range PHEV and E85 ethanol vehicles from the vehicle emission standard + Exclude hydrogen ICE vehicles from vehicle emission standard + Remove all biofuel vehicles</td>
<td>72% 0% 45</td>
<td>70,004,548</td>
<td>72,207,816</td>
<td>185</td>
<td></td>
</tr>
<tr>
<td>1-22</td>
<td>Exclude extended-range PHEV and E85 ethanol vehicles from the vehicle emission standard + Exclude hydrogen ICE vehicles from vehicle emission standard + Pessimistically high battery cost</td>
<td>2% 0% 46</td>
<td>20,543,148</td>
<td>22,649,580</td>
<td>136</td>
<td></td>
</tr>
</tbody>
</table>

53 In simulations 1-9 and 1-10, the emissions given by CIMS are incorrect, because the electricity sector is disconnected from the rest of the model (to achieve exogenous electricity prices)
Table C-3: Results for 'Delayed Entry Hydrogen Fuel Cells' Scenarios (Series 2)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>New Market Share of H Cars &amp; Trucks within VES in 2050</th>
<th>HICE vehicles - All H vehicles in 2050</th>
<th>Hydrogen Price in 2050</th>
<th>Transportation Hydrogen Demand in 2050</th>
<th>Total Hydrogen Demand in 2050</th>
<th>GHG emissions (Mt) in 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1 Base case II</td>
<td>13%</td>
<td>99%</td>
<td>35</td>
<td>63,641,408</td>
<td>66,543,388</td>
<td>133</td>
</tr>
<tr>
<td>2-2 Remove all biofuel vehicles</td>
<td>41%</td>
<td>98%</td>
<td>26</td>
<td>368,141,824</td>
<td>376,218,304</td>
<td>176</td>
</tr>
<tr>
<td>2-3 Exclude extended-range PHEV and E85 ethanol vehicles from the vehicle emission standard</td>
<td>0%</td>
<td>0%</td>
<td>46</td>
<td>18,623,804</td>
<td>20,728,426</td>
<td>133</td>
</tr>
</tbody>
</table>

Table C-4: Results for Lower Progress Ratio Scenario (Series 2)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>New Market Share of H Cars &amp; Trucks within VES in 2050</th>
<th>HICE vehicles - All H vehicles in 2050</th>
<th>Hydrogen Price in 2050</th>
<th>Transportation Hydrogen Demand in 2050</th>
<th>Total Hydrogen Demand in 2050</th>
<th>GHG emissions (Mt) in 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 HFC and HFCPHEV with faster PR (0.5)</td>
<td>14%</td>
<td>95%</td>
<td>35</td>
<td>63,764,884</td>
<td>66,667,372</td>
<td>133</td>
</tr>
<tr>
<td>Scenario</td>
<td>New Market Share of H Cars &amp; Trucks within VES in 2050</td>
<td>HICE vehicles + All H vehicles in 2050</td>
<td>Hydrogen Price in 2050</td>
<td>Transportation Hydrogen Demand in 2050</td>
<td>Total Hydrogen Demand in 2050</td>
<td>GHG emissions (Mt) in 2050</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------------------------------------</td>
<td>----------------------------------------</td>
<td>------------------------</td>
<td>---------------------------------------</td>
<td>-------------------------------</td>
<td>----------------------------</td>
</tr>
<tr>
<td>3-1</td>
<td>Base case III</td>
<td>32%</td>
<td>37%</td>
<td>32</td>
<td>106,998,856</td>
<td>110,439,072</td>
</tr>
<tr>
<td>3-2</td>
<td>Remove vehicle emission standard</td>
<td>11% (0% of all cars &amp; trucks)</td>
<td>76%</td>
<td>46</td>
<td>16,099,360</td>
<td>18,222,116</td>
</tr>
<tr>
<td>3-3</td>
<td>Remove all CO₂ capture and storage</td>
<td>18%</td>
<td>28%</td>
<td>53</td>
<td>45,205,029</td>
<td>47,181,968</td>
</tr>
<tr>
<td>3-4</td>
<td>Instant mature cost for hydrogen infrastructure and production</td>
<td>43%</td>
<td>41%</td>
<td>22</td>
<td>507,109,024</td>
<td>631,831,488</td>
</tr>
<tr>
<td>3-5</td>
<td>Optimistically low hydrogen infrastructure cost + Instant mature cost for hydrogen infrastructure and production</td>
<td>47%</td>
<td>42%</td>
<td>19</td>
<td>571,594,056</td>
<td>807,326,592</td>
</tr>
<tr>
<td>3-6</td>
<td>Double the price of ethanol and biodiesel</td>
<td>64%</td>
<td>36%</td>
<td>25</td>
<td>413,640,024</td>
<td>431,644,832</td>
</tr>
<tr>
<td>3-7</td>
<td>Remove all biofuel vehicles</td>
<td>66%</td>
<td>34%</td>
<td>25</td>
<td>415,350,032</td>
<td>425,195,968</td>
</tr>
<tr>
<td>3-8</td>
<td>Optimistically low battery mature cost</td>
<td>14%</td>
<td>24%</td>
<td>39</td>
<td>42,625,783</td>
<td>45,240,932</td>
</tr>
<tr>
<td>3-9</td>
<td>Pessimistically high battery mature cost</td>
<td>48%</td>
<td>43%</td>
<td>25</td>
<td>371,095,968</td>
<td>381,174,208</td>
</tr>
<tr>
<td>3-10</td>
<td>Pessimistically high hydrogen vehicle mature cost</td>
<td>4%</td>
<td>65%</td>
<td>44</td>
<td>25,401,986</td>
<td>27,603,248</td>
</tr>
<tr>
<td>3-11</td>
<td>Optimistically low hydrogen vehicle mature cost</td>
<td>78%</td>
<td>58%</td>
<td>26</td>
<td>368,811,574</td>
<td>376,815,712</td>
</tr>
<tr>
<td>3-12</td>
<td>Optimistically low hydrogen vehicle intangible cost</td>
<td>70%</td>
<td>39%</td>
<td>25</td>
<td>371,095,968</td>
<td>381,174,208</td>
</tr>
<tr>
<td>3-13</td>
<td>Optimistically low hydrogen vehicle mature cost + Optimistically low hydrogen vehicle intangible costs</td>
<td>95%</td>
<td>62%</td>
<td>24</td>
<td>576,746,736</td>
<td>592,028,736</td>
</tr>
<tr>
<td>3-14</td>
<td>Remove vehicle emission standard + Optimistically low hydrogen vehicle mature cost + Optimistically low hydrogen vehicle intangible costs</td>
<td>100% (86% of all cars &amp; trucks)</td>
<td>70%</td>
<td>25</td>
<td>933,053,152</td>
<td>942,550,784</td>
</tr>
<tr>
<td>3-15</td>
<td>Optimistically low battery mature cost + Optimistically low hydrogen vehicle mature cost</td>
<td>53%</td>
<td>43%</td>
<td>28</td>
<td>225,844,944</td>
<td>230,884,736</td>
</tr>
<tr>
<td>3-16</td>
<td>Pessimistically high battery mature cost + Pessimistically high hydrogen vehicle mature cost</td>
<td>7%</td>
<td>72%</td>
<td>41</td>
<td>34,924,290</td>
<td>37,324,480</td>
</tr>
</tbody>
</table>