Societal Lifetime Cost Comparison of Hydrogen Fuel Cell Vehicles and Gasoline Vehicles

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ABSTRACT

Various alternative fuels and vehicles have been proposed to address transportation related environmental and energy issues such as air pollution, climate change and energy security. Hydrogen fuel cell vehicles (FCVs) are widely seen as an attractive long term option, having zero tailpipe emissions and much lower well to wheels emissions of air pollutants and greenhouse gases than gasoline vehicles. Hydrogen can be made from diverse primary resources such natural gas, coal, biomass, wind and solar energy, reducing petroleum dependence. Although these potential societal benefits are often cited as a rationale for hydrogen, few studies have attempted to quantify them.

This research attempts to quantify the societal benefits of hydrogen and FCVs, as compared with gasoline vehicles and examines how this affects transition timing and costs for hydrogen FCVs. We employ societal lifetime cost as an important measure for evaluating hydrogen fuel cell vehicles (FCVs) from a societal welfare perspective as compared to conventional gasoline vehicles. This index includes consumer direct economic costs (initial vehicle cost, fuel cost, and operating and maintenance cost) over the entire vehicle lifetime, and considers external costs resulting from air pollution, noise, oil use and greenhouse gas emissions over the full fuel cycle and vehicle lifetime. Adjustments for non-cost social transfers such as taxes and fees, and producer surplus associated with fuel and vehicle are taken into account as well.

We employ a learning curve model for fuel cell system cost estimates. The delivered hydrogen fuel cost is estimated using the UC Davis SSCHISM hydrogen supply pathway model, and most vehicle costs are estimated using the Advanced Vehicle Cost and Energy Use Model (AVCEM). To estimate external costs, we use AVCEM and the Lifecycle Emissions Model (LEM). We estimate upstream air pollution damage costs with estimates of emissions factors from the LEM and damage factors with a simple normalized dispersion term from a previous analysis of air pollution external costs. To account for uncertainties, we examine hydrogen transition costs for a range of market penetration rates, externality evaluations, technology assumptions, and oil prices. Our results show that although the cost difference between FCVs and gasoline vehicles is initially very large, FCVs eventually become lifetime cost competitive with gasoline vehicles as their production volume increases, even without accounting for externalities. High valuation of externalities and high oil prices could reduce hydrogen transition costs by more than $10 billion and make hydrogen FCVs achieve cost competitiveness sooner relative to our reference case.

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Chapter 1 Overview of the research

1.1 Research background, motivation and objectives

Current transportation systems face serious and growing challenges, with respect to energy supply adequacy and security, impacts of air pollution on human health and emission of greenhouse gases (GHGs) linked to climate change.

Roughly 97% of all transportation fuels are still dependent on non-renewable petroleum resources. However, the extraordinary concentration of the world oil's supply in a small group of oil producers (e.g., the Middle East) with considerable market power to influence the world oil prices and limited alternative fuels as well as growing energy demand from developing countries have posed a significant issue for the global politics and economy. In the U.S., the largest oil consumer in the world, the transportation sector accounts for around two-thirds of oil consumption (Romm, 2004). U.S. oil imports have grown rapidly since the 1970's, reaching 60 percent of domestic consumption by 2005. Since then, U.S. dependence on petroleum imports had declined slightly, but the net import share of U.S. oil consumption is expected to stabilize at 50% by 2020 (EIA AEO 2008). From 1970 to 2004, the cumulative direct economic costs of oil dependence – including wealth transfer, potential GDP loss, and macroeconomic adjustment, but excluding the military expenditures on oil supplies protection - exceed $2.9 trillion constant 2005 dollars (Greene, 2005). Especially, persistent oil price shocks will have a ripple effect throughout the economy, resulting in more economic losses.

In addition to the economic impacts of oil dependence, conventional oil extraction, production, and end-use in the transportation sector remain one of the largest sources of urban air pollution and GHG emissions. These two major environmental externalities directly and indirectly impact human health, reduce visibility, and lead to crop losses, forest damage, water pollution and climate change damage. From the perspective of environmental economics, these externalities, not priced in the current markets, cause the social cost of owning and operating a gasoline vehicle to exceed the private cost. Delucchi (1998) estimated the social costs (nonmonetary externalities including air pollution and climate change)[1] of motor-vehicle use including upstream emissions to be in the range of $44-$655 billion per year in constant 2005 US dollars.

Energy insecurity, environmental protection and high oil prices have spurred an increased interest in developing alternative fuel/propulsion systems. Compressed Natural Gas (CNG), synthetic diesel, methanol, ethanol, Liquid Petroleum Gas (LPG), Liquefied Natural Gas (LNG), F-T liquids, hydrogen and electricity have been widely discussed as transportation fuels for a switch from petroleum to a more sustainable fuel (MacLean, 2003). Various powertrain options include spark ignition (SI) engine,

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[1] These costs include the environmental, economic and health damages stemming from 1990/1991 levels of air pollution, climate change damages in the U.S. (later we explain the difference between the U.S. and the global perspective), and water-pollution damages. The air-pollution damages from current motor-vehicle emissions might be lower, but probably not dramatically lower, because while total motor-vehicle air-pollutant emissions have declined substantially since 1990 (EPA, 2008), total exposed population and per-capita income (which affects the per-person willingness to pay to avoid the affects of air pollution) have increased. Climate-change damages from current motor-vehicle use, which are a function of total travel and total wealth, are much higher today.

compression ignition (CI) engine, battery-electric systems, fuel-cell electric systems, and hybrid electric-engine systems. According to recent assessments (MacLean et al., 2003, Bandivadekar et al., 2008, US DOE 2007 and 2009), no single fuel/vehicle pathway will lead to improvements in all metrics, which means that a comparative evaluation of vehicle alternatives will have to assess tradeoffs among fuel economy, vehicle performance, range, cost, emissions, and other externalities. However, electric drive vehicles stand out as offering high efficiency, low emissions and the ability to utilize diverse primary resources (IEA, 2008) though the commercialization of such advanced environmental-friendly vehicles will require policy support and technological innovations, overcoming multiple technical and practical hurdles.

For fuel choices to make vehicles more environmentally friendly, replacing gasoline with a zero-carbon fuel would be an ideal long-term solution to problems of energy demand, air pollution and GHG emissions. Hydrogen, with zero emission from fuel-cell vehicle operation, has been extensively debated by regulators, environmentalists, policymakers and automakers as a potential pathway toward sustainable transportation and away from petroleum dependence. Among a variety of fuel/engine combinations, hydrogen fuel cell vehicles (FCVs) seem to have the lowest externalities though facing enormous barriers to achieve significant market penetration in the near-term.

One metric for assessing alternatives is the societal lifetime cost, which includes the vehicle retail cost (a function of vehicle performance), the cost of energy use (a function of vehicle fuel economy),operating and maintenance costs, external costs of oil use, damage costs of noise and emissions from air pollutants and GHGs, and other factors. These costs are estimated over the full fuel cycle and entire vehicle lifetime (Ogden, 2004) and include adjustments for non-cost social transfers such as taxes and fees, and producer surplus associated with fuel and vehicles (Delucchi, 2004).

Although the potential societal benefits from energy supply and environmental impacts are often cited as a rationale for hydrogen, few studies have attempted to quantify them and compare with gasoline fuel for total societal cost. This research builds upon previous studies, estimates the societal lifetime costs in great details for hydrogen FCVs and conventional gasoline vehicles, and attempts to answer the following questions:

- How much is a hydrogen fuel-cell vehicle cost to consumer in the early stage of FCVs market introduction?
- What is the magnitude of total consumer lifetime cost of a hydrogen fuel-cell vehicle as compared with a conventional gasoline vehicle?
- What is the magnitude of externalities and other social costs for FCVs as compared with gasoline vehicles?
- Will societal benefits of hydrogen and FCVs make these vehicles more competitive with gasoline vehicles?

- How do these societal benefits affect transition timing and costs for hydrogen FCVs?
- How will gasoline prices and valuation of externalities affect the competitiveness of hydrogen FCVs?

The overarching objective of the research is to provide an important reference for policy development and industry investment decisions on hydrogen and FCVs by means of comparing FCVs on a consumer/societal lifetime cost basis with gasoline vehicles and estimating the buy-down cost of hydrogen FCVs (cumulative incremental expenditures to bring down hydrogen FCV technology to societal-lifetime cost parity with competitors).

1.2 Research framework and societal lifetime cost concept

The research begins with an extensive review of recent studies on various alternative fuel/propulsion options, particularly focusing on cost estimates for hydrogen FCVs including direct costs, external costs and societal costs. We compare these studies and point out their deficiencies, which provide a clear motive to conduct a self-consistent research on societal lifetime cost estimates for assessing hydrogen FCVs comprehensively, as compared with conventional gasoline vehicles.

Societal lifetime cost is defined as the sum of consumer lifetime cost and external costs over the full fuel cycle and entire vehicle lifetime with adjustments for non-cost social transfers. This concept considers the direct economic costs (vehicle, fuel, and operating and maintenance cost) over the vehicle lifetime and the externality costs resulting from air pollution, noise, oil use and GHGs over the full fuel cycle and vehicle lifetime, as well as social wealth transfers. We consider two different accounting stances: a U.S. perspective and a global perspective, for estimating producer surplus associate with fuel and external costs of oil use and GHGs.

Unlike gasoline, hydrogen is not widely distributed to vehicles today, and fuel cell vehicles are still in the demonstration phase. Understanding hydrogen transition issues is the key for assessing the promise of hydrogen. We have developed several models to address the issues associated with transition costs, in particular, high fuel cell system costs and large investments for hydrogen infrastructure in the early stages of a transition to hydrogen. We analyze three different scenarios developed by the US DOE for hydrogen and fuel cell vehicle market penetration from 2010 to 2025.

We employ a leaning curve model characterized by three multiplicative factors (technological change, scale effect, and learning-by-doing) for key fuel cell stack components and auxiliary subsystems, to estimate how fuel cell vehicle costs change over time. The delivered hydrogen fuel cost is estimated using the UC Davis SSCHISM hydrogen supply pathway model, and most vehicle costs are estimated using the Advanced Vehicle Cost and Energy Use Model (AVCEM) (Delucchi, 2005).

To estimate external costs, we use AVCEM and the Lifecycle Emissions Model (LEM) (Delucchi, 2003). We estimate upstream air pollution damage costs with estimates of emissions factors from the LEM and damage factors with a simple normalized dispersion term from a previous analysis of air pollution external costs. Producer surplus associated with gasoline fuel is modeled in detail with recent data from American Petroleum Institute and the U.S. Energy Information Administration (EIA).

This approach allows us to estimate the total societal lifetime cost of hydrogen FCVs compared to gasoline vehicles, and to examine our research questions.

1.3 Overview of the dissertation

Chapter 2 describes an extensive literature review and summarizes all the relevant studies for their deficiencies which this research attempts to fill in. Hydrogen FCV related literatures are categorized into four sub-sections, including well-to-wheel energy use and emissions, hydrogen transition studies, externalities studies and estimates of societal costs of alternative fuel vehicles.

Chapter 3 provides the societal lifetime cost modeling framework. Chapters 4, 5 and 6 are the central sections, addressing three different aspects of the societal lifetime costs of hydrogen FCVs. Chapter 4 presents the detailed estimates of fuel cell system cost with a three-factor learning curve model and hydrogen onboard storage system cost estimates, where catalyst (platinum) price is modeled in great detail. The Chapter reviews the current fuel cell performance and technological progress in the near term. AVCEM is then updated for fuel cell performance and component cost estimates. With other vehicle costs estimated in AVCEM, we obtain the vehicle cost for a hydrogen fuel cell vehicle under three scenarios from US DOE. We compare our vehicle cost with other studies.

Chapter 5 discusses the external costs, including damage costs from air pollution, oil use, noise and GHGs, in which air pollution damage costs are estimated separately for emissions from motor-vehicles and emissions from the upstream lifecycle of fuels. Upstream air-pollution damage costs were not included in AVCEM. The external costs of oil use are calculated with external cost per gallon of petroleum and vehicle fuel economy based on extensive analyses by Delucchi and Leiby. Damage costs of noise from hydrogen FCVs are assumed to be slightly lower than those from gasoline vehicles. Climate-change damage costs from GHG emissions are estimated for both US and global perspectives according to literature. The four external costs are shown as low, medium and high estimates because of large uncertainties.

Chapter 6 presents the considerations of non-cost social transfers where producer surplus associated with gasoline use in the US is estimated by detailed econometric models. Taxes and fees are calculated in AVCEM and included in the consumer lifetime cost. These costs are deducted for societal lifetime cost calculation because they are transfers, not social costs. For the producer surplus for vehicle purchase, we use the results in AVCEM directly. We describe the societal lifetime cost estimate and the buy-down cost methodology, and perform the sensitivity analysis in Chapter 7, which focuses on the hydrogen transition timing and costs, and the effects of oil prices and externality valuations on the competitiveness of hydrogen FCVs.

The last one - chapter 8 - concludes the research, discusses policy implications, and raises some related questions for further study.

Chapter 2 Literature review

A number of recent studies assess the viability of various alternative fuel vehicles as potential solutions to problems such as energy insecurity, air pollution and global warming. Most studies focus on energy use, emissions of air pollution and greenhouse gases, and direct cost estimates though a couple of studies provides rough calculations for externality costs for air pollution, GHGs and oil supply insecurity. Strictly the full costs of transportation alternatives involve many categories, in which externality costs are often overlooked. A recent comprehensive study by Victoria Transport Policy Institute (VPTI, 2009) shows that external costs are about one-third of total and internal-fixed costs are about a quarter for an average car in North America. Here the external costs include a wide range of environmental impacts and other externalities such as congestion, external crash, road facilities, and so forth. External costs from air pollution, GHGs, noise, resources, land use, and water pollution can be the same magnitude as other externalities. When comparing different vehicle options, we treat other externalities as the same across options because they do not make any significant difference. Below is an extensive literature review on cost analysis for alternative vehicles with focus on those recent ones that analyze hydrogen FCVs and estimate costs for fuels and/or vehicles.

2.1 Well-to-wheel Energy Use and Emissions Studies

The Greenhouse gases, Regulated Emissions, and Energy use in Transportation

(GREET) model (Wang, 1999) developed at Argonne National Laboratory estimates the full fuel-cycle energy use and emissions associated with various transportation fuels and advanced vehicle technologies. The results involve three subcategories: feedstock, fuel, and vehicle operations (passenger cars and two types of light-duty trucks). Emissions output includes five criteria pollutants and GHGs, and energy use involves all energy sources. To examine the Well-to-wheel (WTW) energy and emission impacts of fuel choices for FCVs, Wang (Wang, 2002) used the GREET model to evaluate various fuel-cell fuels and concluded that energy and GHG emission effects of using different fuel options for FCVs can be significantly different and hydrogen produced from electrolysis consumes much energy. GREET 2.7 has incorporated vehicle-cycle model. The GREET model has been widely used for well-to-wheel emissions.

Considering the full fuel cycle from resource recovery to vehicle operation to compare future conventional vehicle, hybrid electric vehicle, and FCV with or without onboard fuel processors, and selecting a GM full-size pickup truck as the baseline vehicle, GM cooperated with Argonne National Laboratory, BP Ameco, ExxonMobil and Shell on a study of well-to-wheel energy use and GHG emissions of 27 fuel pathways, incorporating the results of a proprietary vehicle model by GM and concluded that diesel hybrid, gasoline reformer fuel cell hybrid and hybrid fuel cell fueled with gaseous hydrogen from natural gas have the lowest energy consumption, and vehicles fueled with ethanol from cellulose has the lowest WTW greenhouse gas emissions (GM/Argonne, 2001). No emissions of criteria pollutants were considered in the study. All studied pathways involve a range of estimated data and probability distribution from Monte Carlo analyses that remain considerable uncertainties.

As an update and supplement to a previous North American study by GM/Argonne, the new report by GM, Argonne National Laboratory, and Air Improvement Resource Incorporation (2005) included criteria pollutant emissions, refined the vehicle modeling for energy use, and added more propulsion systems. A 2016-model-year, full-sized GM pickup truck was modeled to estimate the energy use and emissions over its lifetime. Emissions factors from major WTT process were obtained from the U.S. Environmental Protection Agency’s National Emissions Inventory (EPA’s NEI) database and process throughout data, and then the distributions of expected emissions in 2016 were developed based on an assessment of future stationary source emissions controls. On the vehicle side, each propulsion option should meet an assumed emission certification level for 2010. EPA’s MOBILE and California’s EMFAC models were used for modeling the criteria pollutants from vehicle use, and 80% of the vehicles would fall into the two estimates. The vehicle fuel economy over a combined U.S. urban/highway driving cycle was estimated by a GM modeling tool for simulations in GREET. All propulsion systems have equivalent vehicle performance with sized powertrains and components. The WTW analysis concludes that WTT activities could be a large share of WTW emissions of criteria pollutants, especially for alternative fuels, and to address transportation energy and environmental issues, we should consider both fuel and vehicle sides. However, there is no consideration of cost and market penetration of the fuel/propulsion options. Besides, the results depend upon probability functions specifications for key input parameters.

The Laboratory for Energy and the Environment at MIT conducted a series of comparative analyses with a primary focus on lifecycle energy use and GHG emissions for automotive powertrain options in the near- and mid-term future (MIT, 2000, 2003, 2007 and 2008). A typical mid-size passenger car (Toyota Camry) was chosen as a reference. They assumed that both fuel and vehicle would undergo evolutionary improvements over time. Vehicle performance calculations were done by using ADVISOR software developed by AVL, and cost/price estimates were based on a literature review and on consultations with industry experts. These studies concluded that no single "silver bullet" among the technology options available can achieve dramatic reductions in energy use and GHG emissions, and that a strategy called "Emphasis on Reducing Fuel Consumption" (ERFC) will play a significant role in reducing fuel consumption in the U.S. ERFC is defined as the ratio of FC reduction realized on road to FC reduction possible with constant performance and size. This measures the degree to which technological improvements are being directed toward increasing onboard vehicle fuel economy. These studies focused on direct economic costs and GHG emissions, but did not estimate external costs per se.

As a successor to their 2000 report "On the Road in 2020", Bandivadekar et al. (2008) extended the timeframe from 2020 to 2035 for quantitatively assessing more efficient propulsion systems targeted at light-duty fleet petroleum consumption and GHG emissions reduction in terms of the timing and impact. The focus is the United States, but several European countries are included. Seven propulsion systems were studies in the report: the naturally-aspired spark-ignition vehicle (NA-SI), the turbocharged spark-ignition vehicle (turbo), the compression-ignition diesel vehicle (CI), the gasoline hybrid-electric vehicle (HEV), the plug-in hybrid (PHEV), the fuel cell hybrid vehicle, and the battery-electric vehicle (BEV). Future vehicles are assumed to have constant size (cross-sectional area) and performance (acceleration time) at the level of representative 2005 models. The representative car is a 2.5-liter Toyota Camry and the representative light-truck is a 4.2-liter Ford F-150. Still, ADVISOR software was used for the vehicle system simulations. Scaling laws are applied for estimating the evolution of individual vehicle components according to extensive literature review. The lifecycle analysis includes the well-to-tank, tank-to-wheel, and vehicle manufacturing and end-of-life disposal and GHG emissions with the vehicle-cycle impact evaluated from GREET. For future vehicles, it is assumed that weight reduction is from use of lightweight materials. Future vehicle cost estimates were from Kromer 2007. To identify options for a significant reduction of light-duty vehicle fleet consumption and GHG emissions, an in-use vehicle fleet model was developed to "examine scenarios with various combinations of propulsion system and vehicle technologies, the evolving production volumes of these technologies, and increasing amounts of alternative fuels." These developed scenarios consider major barriers to market acceptance including both supply-side and demand-side constraints. Due to a high degree of technical and cost uncertainty, hydrogen fuel cell vehicles (FCVs) were excluded from the scenario analysis for market penetration of advanced vehicles. An important concept of Emphasis on Reducing Fuel Consumption (ERFC) was introduced to quantify the trade-offs among vehicle performance, size, and fuel consumption. This report concludes that "all current powertrains recover their retail price increase at higher gasoline prices of $4.50 per gallon" assuming 7% discount rate over a 15-year lifetime, ERFC has significant influence on reducing fuel consumption in the United States, reducing GHG emissions is more challenging than reducing fuel use because of the life-cycle impacts, and no "silver bullet" in the technology options available can achieve dramatic reductions in energy use and GHG emissions.

A joint European study was conducted by EUCAR, CONCAWE and JRC (EC, 2007) on WTW energy use and GHG emissions associated with a wide range of automotive fuel and powertrain options for European countries in 2010 and beyond. The study assessed the potential benefits resulting from alternative fuels replacing conventional fuels. A common vehicle platform (a compact five-seater 2002 European 2002) was used as a reference for comparison. The EUCAR members assumed that the vehicle fuel efficiency beyond 2010 would have a certain percentage improvement over the reference. Various vehicle options were assumed to comply with the minimum set of performance criteria and pollutant emission regulations in force in Europe (EURO III for 2002 and EURO IV for 2010 on). Using ADVISOR, the group simulated fuel consumptions and GHG emissions under European type-approval driving cycles. Macroeconomic costs to the EU, expressed as the cost of fossil fuels substitution and CO_2 avoided, were estimated under two separate cost scenarios for crude oil prices of 25 and 50 € /bbl. Given the 2010-2020 horizon in this study, a limit of 10-15% substitution level was set for alternative fuels and an incremental approach was performed to estimate the savings from the substitution in a marginal way for the difference calculation between two future scenarios (business-as-usual versus alternative). By-product credits are included as well. For vehicle-related cost, the retail price increment expected beyond 2010 was estimated for the various technologies based on a review of the recent literature. No maintenance costs were considered. This study indicates that "a shift to renewable/low fossil carbon routes may offer a significant GHG reduction potential but generally requires more energy," and a portfolio of various fuels may be expected in the market.

Granovskii et al (2006) at University of Ontario Institute of Technology (UOIT) used various published data to compare conventional, hybrid, electric and hydrogen fuel cell vehicles from both economic and environmental perspectives, including fuel utilization and vehicle production and utilization stages under three different electricity production scenarios. The four vehicle options were compared according to economic indicators (vehicle price, fuel costs and driving range), and environmental indicators (air pollution and GHG emissions) for the years 2002 to 2004. Each indicator was normalized so that a value of 1 represented the best economic and environmental performance among the cars considered. The ratios of each car's performance to the best performance gave the normalized indicators for each performance category. The product of the calculated normalized indicators was the overall indicator for each car type. The analysis shows that hybrid and electric cars perform better than the other options and that the electricity generation mix substantially affects the economics and environmental impacts of electric cars. They also found that on-board electricity generation from a fuel-cell system would improve the economic and environmental ranking of electric cars. However, inconsistent data used in the study, subjective choice of indicators, the simple normalization procedure, and a lack of other evaluation criteria (such as externalities costs) limit the generalization of the conclusions.

2.2 Hydrogen Transition Studies

To evaluate the three hydrogen and FCVs market penetration scenarios developed by the US DOE, Greene et al. (2008) at Oak Ridge National Laboratory (ORNL) analyze hydrogen infrastructure and deployment with the DOE's integrated market simulation model (HyTrans). They evaluated policy options to support the transition to hydrogen-powered transportation, and estimated the costs associated with policy implementation. Two key economic barriers were addressed: the current lack of hydrogen infrastructure and the high cost of FCVs at low production volumes. Hydrogen production pathway costs were obtained by using HYPRO model from Directed Technologies, Inc. (DTI). Their analysis assumes the DOE technical targets are met, meaning that fuel cell vehicle systems would achieve $45/kW by 2010 and $30/kW by 2015 in the laboratory with a five-year time lag for implementation in mass production. A composite learning curve was used to model how drivetrain production costs would decrease as a function of technological progress and production volumes. Glider costs are taken as constant for all technology types. The study indicates that targeted deployment policies could allow the FCV market share to grow to 50% by 2030 and 90% by 2050, and that beyond 2025 no policy support would be needed for a sustainable, competitive market for hydrogen FCVs. The estimated cumulative costs of alternative government policies for a successful transition to hydrogen FCVs were from $10 to $45 billion for the period from 2012 to 2025.

Using the ORNL learning curve model and the UC Davis SSCHISM, the NRC (2008) presents several hydrogen scenario analyses in detail. They project potential reductions in petroleum use and carbon dioxide emissions in 2020 and beyond, the investments needed to bring hydrogen FCV technologies to cost competitiveness with gasoline vehicle technology, and the costs for a future hydrogen infrastructure. For the “Hydrogen Success” scenario, the Committee concludes that “oil displacement is about 0.8 percent in 2020, rising to 24 percent in 2035 and 69 percent in 2050,” and

GHG emissions reduction is about 0.7 percent in 2020, 19 percent in 2035, and 60 percent in 2050. The investment costs (the difference in vehicle prices plus the difference in fuel costs) for hydrogen FCVs to reach cost competitiveness are about $22 billion though this number depends on many key assumptions. The estimated cost of fully building out hydrogen supply to fuel 220 million FCVs by 2050 is more than $400 billion.

2.3 Externalities Studies

To provide policy-makers with a substantiated scientific background, the ExternE (External costs of Energy) European socio-economic research (2003) has developed the energy-economy-environment models for scenarios analysis of cost effectiveness, evaluated the socio-economic impacts of the policies and measures to address the climate change issue, and conducted the monetary quantification of external costs from energy production and consumption. The project has already considered seven major types of damages including human health (mortality and morbidity), building material, crops, global warming, amenity losses, and ecosystems, and the scope is expected to expand. The core of the ExternE project for environmental benefits and costs estimates is a detailed bottom-up impact pathway approach that traces the impacts from source emissions to physical impacts by dispersion and dose-response function. Thus, the change in concentration of pollutants between the initial (reference case) and after-change case (scenario) is linked to the differences in physical impacts on human health, crops, ecosystems et cetera. Finally, based on welfare theory, the physical impacts are quantified in monetary terms though with large uncertainties for the monetary values. This methodology has been widely applied for European and national studies, such as a comparison of damage costs per kWh for coal, gas, nuclear, and wind electricity, and a comparison of damage costs between transport modes. The latter includes the air pollution costs from vehicle use, vehicle production, fuel production and infrastructure due to urban passenger transport (bus and car). Rabl and Spadaro (2000) applied the method to analyze the external costs of the major energy technologies and concluded that the classic air pollutants from fossil fuels impose significant public health costs.

Researchers (Colella et al., 2005, Jacobson et al., 2005) at Stanford University used GATOR-GCMOM model and National Emission Inventory (NEI) for examining the potential change in primary emissions from establishing a hydrogen economy that replaces the current U.S. fossil-fuel vehicle fleet with hydrogen FCVs, and considered three hydrogen pathways with hydrogen produced from steam reforming of natural gas, wind electrolysis and coal gasification. Their analysis shows all hydrogen FCVs scenarios with a range of reasonable FCV efficiencies and hydrogen production methods would achieve significant reduction in air pollutant emission. They also concluded that the greatest potential health benefits are provided by wind and natural gas hydrogen FCVs that could save 3700 to 6400 U.S. lives annually. Total health and climate cost reductions from natural gas hydrogen FCVs may be in the range of

$33-$248 billion per year in the U.S.

For comparison of major energy-related solutions to global warming, air pollution, and energy security under the U.S. conditions in 2020, Jacobson (2008) ranked twelve energy source-vehicle options from the combinations of nine electric power sources and two liquid fuels with three types of vehicles (BEVs, HFCVs, and E85 FFVs) using eleven impact categories. The impacts include resource abundance, lifecycle CO_2-equivalent emission, mortality, footprint, spacing, water consumption, effects on wildlife, thermal pollution, water chemical pollution/radioactive waster, energy supply disruption, and normal operating reliability. ESI (Electronic Supplementary Information) and a number of other studies are the data sources. Each impact category was weighted by its relative importance to obtain an overall ranking of each technology combination with the highest priority to effects on CO_2-equivalent emissions and mortality. It turns out that wind-BEVs are the best, followed by wind-HFCVs, and Cellulosic-E85 is the worst because of higher upstream air pollution emissions and significant land requirements. The study does not examine costs because the author argues that “policy decisions should be based on the ability of a technology to address a problem rather than costs” and costs of new technologies involve variability and uncertainties.

Recently, UC Irvine (Stephens-Romero et al., 2009) published a study on air quality and GHG impacts of hydrogen infrastructure and FCVs. Assuming FCVs achieve

75% market penetration of passenger vehicle fleet in the South Coast Air Basin of California (SoCAB) in 2060, they apply a "spatially and temporally resolved energy and environment tool" (STREET), and the UCI-CIT atmospheric chemistry and transport model (air quality model) to evaluate two hydrogen scenarios: one with more renewable primary energy sources and the other with more fossil fuel sources for hydrogen generation. Their results show that hydrogen scenarios will lead to substantial improvements in air quality in the SoCAB in parallel with 61-68% GHG emissions reductions. Especially, ozone and particulate matter (greatest concern to human health) are significantly reduced with hydrogen adoption. They also indicate that hydrogen infrastructure and FCVs deployment will be much more advantageous to an urban airshed than remarkable improved ICE and hybrid ICE vehicles in terms of air quality and GHG emissions.

These studies, done at Stanford and UC Irvine, focus on the reductions in air pollution and GHG emission from hydrogen and FCVs. However, they do not analyze other externalities, such as oil dependence.

2.4 Societal Cost Estimates of Alternative Fuel Vehicles

Ogden and colleagues at Princeton University (2004) performed one of the few studies that estimate the total societal cost of various alternatives to petroleum-based fuels. They used the "societal lifecycle cost" (the same as our societal lifetime cost

[SLC]) as a basis for comparing alternative automotive engine/fuel options that are meant to address concerns about air pollution, climate change, and oil supply insecurity. The societal lifecycle cost per vehicle was defined as the sum of vehicle first cost and the present value of lifetime costs for fuel, non-fuel operation and maintenance, full fuel-cycle air-pollutant and GHG damages and oil supply insecurity. They assumed that the fuel infrastructure is fully developed, that all vehicles have the same performance, and that future drivetrains are mass produced. Vehicle first costs and fuel economies were obtained from an extensive literature review. Non-fuel operation and maintenance costs were thought to be the same across all options and so were not included in the analysis. Most estimates of upstream air-pollutant and GHG emissions were from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, and estimates of in-use emissions from advanced vehicles were from other analyses and the authors' calculation. The damage costs from air pollutants and GHG emissions were estimated by adjusting ExternE estimates (Spadaro, 1998 and Rabl, 2000) to U.S. population density (Southern California was chosen as the US norm). Oil supply insecurity cost was simply calculated with the U.S. military expense for Persian Gulf and fraction of Persian Gulf exports to the United States. To account for the uncertainties in these externality valuations, they presented the societal lifecycle cost of several engine/fuel options separately with low, median and high estimates of externality costs. The analysis found that most advanced options have lower lifetime costs than today's new cars when external costs are internalized. And at high valuations of externalities, the hydrogen FCV with hydrogen derived from fossil fuels with sequestration of CO2 would have the lowest lifetime societal cost among all options with the lowest externality costs.

A recent life cycle cost analysis of hydrogen by Lee et al. from South Korea by Lee et al. (2009) examines several key factors for the economical feasibility of hydrogen as an alternative option. Four hydrogen pathways are considered for life cycle cost calculations and compared with conventional fuels. The life cycle cost includes well-to-tank costs, tank-to-wheel costs and external costs from air emissions and GHGs. A base case in 2007 and a future scenario in 2015 are discussed for a Hyundai sport utility vehicle (TUCSON). Data for the fuel pathways are drawn primarily from publications in South Korea and Hyundai Motors. External cost estimates are based on a review of the literature. This study indicates that hydrogen life cycle costs depend on FCV price, production capacity, fuel efficiency, social costs and hydrogen pathways, and that all hydrogen pathways are expected to be economically feasible by 2015.

Another recent study by H2Gen (Thomas, 2008) compares the societal benefits of various alternative transportation options in terms of reductions on local air pollution, GHG emissions, and oil consumption. The analysis includes gasoline, diesel, ethanol, hydrogen, and grid electricity. Twelve different alternative fuel/vehicle combinations are analyzed including battery-powered vehicles, hybrid electric vehicles (HEVs), plug-in hybrids (PHEVs) and FCVs. The GREET model was used to calculate emissions of local air pollution and GHGs, and oil consumption with some GREET input parameters modified to “reflect the changing methods of producing ethanol, hydrogen and electricity, particularly when carbon constraints are introduced.” The unit health costs from urban air pollution or air pollution reduction costs were derived from the average of several estimates in the US and Europe. The GHG damage cost was assumed to be $25 per metric tonne of CO_2 in 2010, increasing linearly to $50/tonne by 2100. A societal cost of $60/barrel was assumed for oil consumption. The analysis concludes that hydrogen FCVs would be the only option to achieve significant GHGs reduction and nearly eliminate all controllable urban air pollution. The only solutions to energy “quasi-independence” would be hydrogen vehicles (fuel cell or hydrogen ICE) and all-electric vehicles. According to the analysis, the societal cost savings from hydrogen FCVs justify the hydrogen infrastructure costs. However, this study didn’t address the consumer cost. Also, averaging external cost estimates for different regions may not be accurate.

Based on detailed computer simulations, Thomas (2009) at H2Gen concludes that all-electric vehicles would be the ultimate solution to achieving the US energy security and climate change reduction goals. Thomas compares FCVs and battery-electric vehicles in terms of weight, volume, GHGs and cost, and finds that fuel cell electric vehicles are superior to advanced lithium-ion battery electric vehicles in most aspects: they weigh less, cost less, emit fewer GHGs, use less WTW energy (with natural gas or biomass feedstocks), and have shorter refueling time. However, battery electric vehicles have lower fuel cost, use less WTW wind or solar energy on a per-mile basis, and in the early years would have greater access to fueling capability.

In contrast with Thomas' conclusion, an earlier study on cost comparison of fuel cell and battery electric vehicles (Eaves, 2004) based on U.S. government studies indicated that a battery electric vehicle (BEV) is more efficient, cleaner, and less expensive in terms of manufacturing and refueling costs. Similarly, a newly published study by Offer et al. (2010) concludes that both BEVs and fuel-cell plug-in hybrid vehicles (FCHEV) would have significantly lower lifetime costs (capital and running costs) than hydrogen fuel-cell vehicles in 2030. This comparative analysis, based on cost predictions from International Energy Agency and Department of Transport (DfT), assumes a single vehicle platform with 80kW peak power and 20kW mean power. Offer et al. report powertrain (capital) and fuel (running) costs in 2010 and 2030, but do not estimate social costs.

The US DOE Multipath Study (Patterson et al., 2007) assesses eleven pathways and constructs ten scenarios for light-duty-vehicle transportation futures from the perspectives of oil and GHG saved. The study also considers vehicle costs, infrastructure issues, criteria emissions and risk associated with discontinuous development, high costs and unsuccessful market. Their results show that the FCV pathway could have the highest oil savings by 2050. Further work on the Multipath

Study (Plotkin and Singh, 2009) has focused on costs and scenario analysis, using the National Energy Modeling System (NEMS), an automotive system cost model, and oil security metrics model (OSMM). The Multipath study concludes that successful development of advanced vehicle technologies will require strong government intervention unless industry is able to radically reduce costs.

We summarize all the studies that include cost estimates for hydrogen FCVs, as shown in Table 2-1. Most of these studies focus on estimating energy use and GHG emissions for future vehicle options at a specific time point. Some studies consider vehicle initial costs, running costs, and a range of external costs, but some consider vehicle cost only and some include only certain externality costs. In most studies vehicle performance is not modeled explicitly, but in a few studies, performance is simulated with ADVISOR. None of the studies use a detailed cost model for vehicle components to examine key cost drivers; none of them have a combined energy-use and vehicle cost model to ensure consistency between the cost and performance estimates; and none of them consider operating, insurance, and maintenance costs. Some studies use the GREET model to estimate air pollution and GHG emissions without careful examining the default parameters in GREET. Few studies systematically address the damage costs from upstream air pollution, and no studies have a comprehensive estimate of the external costs of oil use.

Table 2-1 Summary of recent studies of the cost and impacts of FCVs and other advanced vehicles

Study group	MIT	ORNL	NRC	EUCAR	UOIT
Region	U.S. and several European countries	U.S.	U.S.	Europe	N.A.
Timeframe	2020, 2030, 2035	2012-2025	2010-2050	2010+	2002-2004
Vehicle type	Mid-size car (Toyota Camry) Light-truck (Ford F-150)	Light-duty vehicle	Light-duty vehicle	Compact 5-seater European sedan	Toyota Corolla, Prius, RAV4 EV, Honda FCX
Fuels	Gasoline, Diesel, CNG, FT diesel, methanol, H2, Electricity	H2	Gasoline, bio-fuel, H2, electricity	Gasoline, diesel, CNG, biogas, LPG, ethanol, bio-diesel, DME, CH2/LH2	Gasoline, electricity, H2
Powertrains	ICE, hybrid, plug-in hybrid, battery, fuel cell	Fuel cell	ICE, hybrid, fuel cell	ICE, hybrid, hybrid fuel + reformer	ICE, Hybrid, battery, fuel cell
Feedstocks	Petroleum, NG, National power grid	NG, coal, biomass, ethanol	Petroleum, NG, coal with CCS, biomass, water, corn, cellulose	Crude oil, NG, biomass, sugar, wheat, cellulose, coal, water	Crude oil, renewable, NG
Vehicle energy-use model	ADVISOR simulation	No formal model	No formal model	ADVISOR simulation for fuel consumptions and GHG emissions	No formal model
Vehicle cost	Retail price and OEM cost estimates from literatures and conversation with industry experts: \$3000-\$5300 for incremental retail price of Future FCV relative to future ICE	Drive train cost estimate by a composite learning curve (HyTrans model) with constant glider cost (assume DOE technical targets are met for fuel cell system)	ORNL learning curve model for estimates of fuel cell vehicle cost and investment costs	Vehicle retail price increment expected beyond 2010 at 50K vehicles per year; maintenance costs not considered	Estimates based on published price projections: Conventional: \$15,300 Hybrid: \$20,000 Electric: \$42,000 FCV: \$100,000 in regular production; 10-year vehicle life

Fuel cost	Sum of 3 steps in fuel cycle for fuel cost estimates in 2020 with large uncertainties	H2 pathway costs from DTI's HYPRO model ($2.5~$3.25/kg)	UC Davis SSCHISM	WTT and TTW costs Only direct costs (related to purchasing feedstocks, building plants, infrastructure and vehicles) included for two cost scenarios, market price for internationally traded resources	Average prices from EIA 1999-2004: Gasoline $1.51/gal Electricity 4.84¢/kwh H2 $1.57/kg assuming same as gasoline on a LHV basis
Vehicle lifecycle	Energy use and emissions from vehicle life cycle	Not included	Not included	TTW approach for energy expended and associated GHG emitted	Not included
Fuel lifecycle	Fuel cycle energy consumption and GHG emissions from published data	Not included	WTW GHG emissions	WTW energy use and GHG emissions	Lifecycle GHG and air pollution from literature review
External costs	Not included	Not included	Not included	Not included	Air pollution and GHG from fuel cycle and vehicle cycle, relative to best vehicle

Table 2-1 Continued

Study group	Ogden	South Korea	Thomas	Offer
Region	U.S. (Southern California)	Korea	U.S.	UK
Timeframe	Not specified	2007, 2015	2005-2100	2010, 2030
Vehicle type	Mid-size automobile (4-5 passengers)	Sport utility vehicle	Light-duty vehicle	Saloon car
Fuels	Gasoline, CNG, diesel, FT50, methanol, H2	H2, gasoline, diesel	Gasoline, diesel, ethanol, hydrogen and grid electricity	Gasoline, hydrogen and grid electricity
Powertrains	ICE, hybrid, fuel cell	ICE, fuel cell	ICE, hybrid, plug-in hybrid, battery, fuel cell	ICE, fuel cell, battery, and fuel cell plug-in hybrid
Feedstocks	Crude oil, NG, coal, wind, water	Crude oil, NG, water	Petroleum, NG, coal, nuclear, renewable, corn,	Petroleum, NG, coal, gas, nuclear and wind

			cellulose, hemi-cellulose, biomass	
Vehicle energy-use model	No formal model	No formal model	No formal model	No formal model
Vehicle cost	Vehicle first cost estimates based on engineering and cost models from several sources (retail costs of drive-train and body); 10-year vehicle life	Vehicle price estimated from the data given by Hyundai Motor Company; 160,000 km vehicle life	Use the cost estimates by Kromer and Heywood at MIT (2007) for FCV and electric vehicle	Powertrain cost data from other reports; 100,000-mile vehicle life
Fuel cost	Lifetime fuel cost calculated from fuel economy and levelized fuel price (8% discount rate, driven 12,000 miles/year, 10 years)	Fuel utilization costs calculated based on fuel efficiency and driving distance with data from Hyundai motors	DOE H2A model H2 cost ($3.33/kg) from NRC study at hydrogen fueling system breakeven point	Optimistic and pessimistic assumptions regarding fuel price, based on literature review
Vehicle lifecycle	Not included	Not included	Not included	Not included
Fuel lifecycle	Full fuel-cycle (WTW) air pollution and GHG emissions considered	WTW costs, regulated air emissions and GHGs from field data, literature and pilot plant data in Korea	WTW energy efficiency, WTW urban air pollution and GHG emissions from GREET model	Not included
External costs	Damage costs from air pollution & GHG emissions and oil supply insecurity costs	Damage or prevention costs from GHGs and regulated air emissions	External costs from urban air pollution, GHG emissions and oil imports	Not included

Chapter 3 Societal lifetime cost modeling framework

This dissertation builds on previous research, attempts to fill in some of the gaps identified in Chapter 2, and answers the questions put forward in section 1.1. We use AVCEM, SSCHISM, and other models to estimate the societal lifetime cost, including both consumer cost and external costs as well as adjustments for non-cost social transfers, for hydrogen FCVs and conventional gasoline internal combustion engine vehicles (ICEVs).

AVCEM (Delucchi, 2005) is a vehicle performance and design model that allows users to design a vehicle to exactly satisfy performance and range specification with no more power and storage than is needed. Cost model is integrated with energy use model so that one can find the design that results in the lowest lifetime costs, with all relevant tradeoffs and factors accounted for explicitly. Vehicle performance, energy use and all costs are modeled in detail within AVCEM, a standalone framework for consistency between the performance and cost estimates. Vehicle operating, insurance, and maintenance costs are also included in consumer cost.

AVCEM is useful for designing a variety of fuel/propulsion options to meet specified vehicle performance and range requirements. The model starts with baseline conventional gasoline vehicle parameters, sizes all the components in the vehicle for a wide range of vehicle types. The model can calculate the initial retail cost and total private and social lifetime cost in present-value terms that include vehicle cost, fuel cost, periodic ownership and operating costs during the whole vehicle lifetime and external costs over the fuel lifecycle. AVCEM provides a self-consistent framework for estimating the societal lifetime cost of various vehicle types. We focus on light duty vehicles, which is the largest transportation subsector, and uses over 60% of US transportation energy. A typical gasoline car similar to 2006 Ford Taurus is selected as our baseline vehicle. The hydrogen FCV version of this vehicle is modeled in detail, with a careful, comprehensive accounting of all of the differences between a hydrogen FCV and a conventional gasoline ICEV. Both consumer lifetime cost (CLC) and external costs are considered. Vehicle fuel economy is calculated using a detailed energy-use simulation within AVCEM given performance requirements and propulsion characteristics. The damage costs from upstream air pollution are treated differently from vehicle-use air pollution. Non-cost social transfers are taken into account for societal lifetime cost estimates from both national and global perspectives.

Figure 3-1 presents the research framework. Consumer lifetime cost includes initial vehicle cost, fuel cost and operation and ownership cost from the time of vehicle purchase to the time of scrappage. External cost takes into account the damage costs of air pollution, oil use, noise, and GHG emissions from the full fuel cycle and vehicle operation. Non-cost social transfers include taxes and fees and producer surplus in revenues from the sale of fuels and vehicles. Producer surplus is an economic measure of the benefit that a producer receives for selling a good in the market; specifically, it is any revenue *above* the total long-run cost including a normal rate of return. To estimate the producer surplus associated with gasoline fuel use in the US, we use econometric models to develop oil supply curves for the US and other regions with detailed drilling cost data from American Petroleum Institute (Joint Association Survey on Drilling Costs 2004), and oil production and rent data from world bank. With some critical assumptions, we then derive gasoline supply curves for producer surplus estimates.

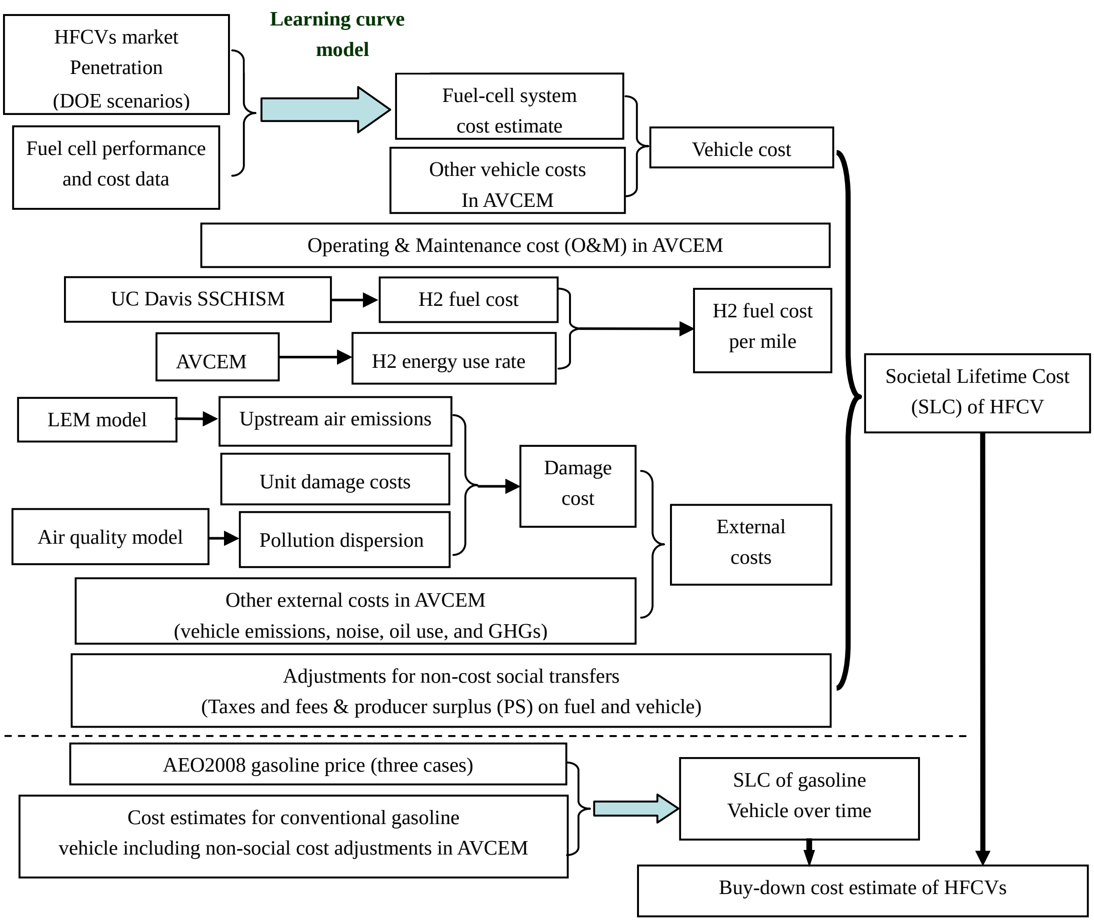


Figure 3-1 Research framework

We use the AVCEM model and additional analysis to estimate the external costs associated with oil use, air pollution, climate change, and noise. Oil-use costs comprise the cost of the Strategic Petroleum Reserve (SPR), macroeconomic costs from oil price shocks, wealth transfers from U.S. consumers to foreign oil producers (a cost only in the U.S. national accounting), the military costs of oil use, and the cost of water pollution due to oil use. Air pollution costs comprise health effects (such as premature mortality), reduced visibility, crop losses, and damages to forests and materials. The external costs of air pollution include the impacts of emissions from the "upstream" lifecycle of fuels as well as emissions from vehicle themselves, and the external costs of climate change include the impacts of emissions from the vehicle lifecycle as well as from the full lifecycle of fuels. The upstream lifecycle of fuels includes energy feedstock production, transportation and storage, and fuel production, transportation, storage and distribution. The vehicle cycle includes vehicle assembly and the lifecycle of materials used in vehicles. Estimates of the damage cost of noise from gasoline vehicles are from a previous study by Delucchi and Hsu (1998). In AVCEM, we assume hydrogen FCVs produce slightly less noise. Estimates of lifecycle CO_2-equivalent GHG emissions are from the LEM. According to recent studies on marginal cost of CO_2 emissions, the climate-change damage cost in dollars per metric ton carbon is assumed to be different for the US and global perspectives.

To account for uncertainties, we examine hydrogen transition timing and costs for a range of market penetration rates, externality evaluations, technology assumptions, and oil prices.

Chapter 4 Hydrogen Fuel Cell Vehicle Cost and performance estimates

AVCEM designs vehicles that meet specific range and performance requirements over a particular drive-cycle, and then calculates the vehicle lifetime cost. Users can specify up to seven different kinds of vehicles for analysis. The baseline conventional gasoline ICEV we choose in AVCEM is equivalent to 2006 Ford Taurus, which is obtained by weight and cost adjustments on 1989 Ford Taurus in AVCEM (Delucchi, 2005). Table 4-1 presents a performance summary of the reference vehicle, and the cost details are included in Table 4-2. The final retail cost to consumer[2] for the baseline gasoline vehicle is $22,198 in 2005 US dollars.

Table 4-1 Performance summary of our baseline gasoline car

Parameter	**Units**	**Value**	**A/C[a]**	**Notes**
Vehicle weight	Kg	1540	C	Actual in-use weight including payload and part-filled fuel tank
Engine power	kW	108	A	3.0 liter 6-cylinder with compression ratio of 9.7
Frontal area	m^2	2.00	A	Assumed according to literatures
Drag coefficient	-	0.25	A	MY2006 Ford Taurus: Cd=0.30
Fixed rolling-resistant	-	0.0075	A	Average of 2006 NA-SI and 2030 value assumed in MIT study (Kromer and Heywood, 2007)
Fuel Economy	MPG	18.6/32.3	C	FUDS/Highway, 2006 Ford Taurus: City (20)/Highway (27)

[a] A = assumed, C = calculated.

[2] This is slightly different from retail price to consumer that includes license fees, all mark-ups and taxes.

Table 4-2 Cost summary of our baseline gasoline car

Component – manufacturing cost	**2005 US $**	**Notes**
Powertrain (engine+transmission)	$1,960	Powertrain adjusted for improvements in power and efficiency and reductions in weight, supposed to a 2006 powertrain
Body	$1,953	Baseline adjusted for changes in safety equipment, drag, and weight, supposed to a 2006 one
Chassis	$3,098	Baseline adjusted for changes in weight, emission control systems, and air conditioning and heating systems, supposed to a 2006 one
Assembly	$1,741	Labor wages based on analysis of industry data; labor time based on previous estimate adjusted for assumed increases in automation
Total manufacturing cost	***$8,752***	***Sum of the above costs***
Division cost	$5,364	Engineering, testing, advertising, etc.; estimated relative to manufacturing cost
Corporate cost	$3,465	Executives, capital, R&D, cost of money and true profit
Dealer cost	$3,446	Dealer margin minus warranty cost
Manufacturers' suggested retail price	$21,027	Manufacturing cost plus division, corporate and dealer costs
Shipping cost	$524	Proportional to vehicle curb weight ($0.16/lb)
Sales tax	$647	Sales tax
Retail cost to consumer	***$22,198***	***Division and corporate costs, profit, dealer cost, shipping cost and sales tax included***

AVCEM starts with vehicle parameters like those in Table 4-1, sizes all the components in the vehicle for a wide range of vehicle types. The model can calculate the initial retail cost and total private and social lifetime cost in present-value terms that include vehicle cost, fuel cost, periodic ownership and operating costs during the whole vehicle lifetime and external costs over the fuel lifecycle. To model the effect of economies of scale, technological progress, and manufacturing progress on the manufacturing cost of key parts such as electric drive-train, battery, fuel cell, hydrogen fuel storage tank and so forth, AVCEM uses a single cost versus annual production volume function. However, this kind of cost function does not manifest technological change and learning-by-doing explicitly. In this study, we treat these three factors (technological progress, economies of scale, and learning-by-doing) separately. For fuel cell system, each component cost is the product of a long-run potential cost and the three factors. Here, technological progress is a time-dependent variable, economies of scale depends on annual production, and learning-by-doing is expressed as a function of cumulative production. This method is similar to the approach in the HyTrans model (Greene, 2007) for estimating fuel cell vehicle drive-train costs.

On the basis of US DOE scenarios for hydrogen and FCV market penetration from 2010 to 2025, we employ a learning curve model with these three factors to estimate fuel cell system cost reduction over time. Following the treatment by the NRC (2008), we estimate hydrogen fuel cost with the UC Davis Steady State City Hydrogen Infrastructure System Model (SSCHISM) (Yang and Ogden, 2008). As a part of consumer cost, vehicle operating and maintenance cost is also included according to the results from AVCEM.

4.1 Fuel Cell System Cost Estimate

Hydrogen fuel cell systems have the potential to be a clean and efficient power option for light-duty vehicle applications to reduce oil dependence and mitigate emissions of air pollution and CO_2. However, there are many technical and economic challenges facing fuel cell commercialization (Ahluwalia, 2008, Zegers, 2006, Mock, 2009). High fuel cell system cost is a serious barrier to a wide acceptance of hydrogen fuel cell vehicles. Extensive research has been undertaken to estimate mass production cost of fuel cell stack or system and examine some key cost drivers (James, 2007, Carlson et al., 2005, Tsuchiya, 2004). A few studies apply learning curves (Tsuchiya, 2004, Lipman, 1999) for modeling fuel cell manufacturing cost reduction with production volume increase, assuming a progress ratio in the range of 70%-90%. The progress ratio shows how the production cost could be reduced for each doubling cumulative production. All the cost analysis takes the catalyst (platinum) price as a constant (current prices).

We define the fuel cell system as including the fuel cell stack and the balance of plant (BOP), but not the hydrogen storage system. This study analyzes hydrogen FCVs that are not hybrids with peak power device such as battery. The fuel cell system cost depends upon fuel cell stack performance, catalyst cost, stack materials, balance-of-plant design, manufacturing process and economies of scale. Several studies (Wang, 2003, Yan, 2006, Na, 2007) have clearly shown that pressure, temperature, humidity and stoichiometry are important parameters that affect fuel cell power output and efficiency. In AVCEM, we specify seven fuel cell polarization curves with data points (voltage vs. current density) from a parametric study (Wang, 2003) under combinations of different cathode pressure and air stoichiometric ratio (shown in Figure 4-1). The balance of plant includes air management, water management, thermal management and fuel management. It is especially important to model the air management system accurately, because it consumes more than 50% auxiliary power. AVCEM assumes a variable-speed compressor and at each point picks the operating regime (compression and stoichiometry) that minimizes the total system energy consumption. To reduce compressor parasitic power requirements, an expander can be included to recover energy from the cathode exhaust for the current technology. However, the benefit is relatively small and does not justify the added cost and complexity of the expander (Ahluwalia, 2008), so we do not include an expander in our analysis. We adjust the system performance to be roughly consistent with the assumptions by Directed Technologies, Inc. (DTI) (James, 2007) as shown in Table 4-3.

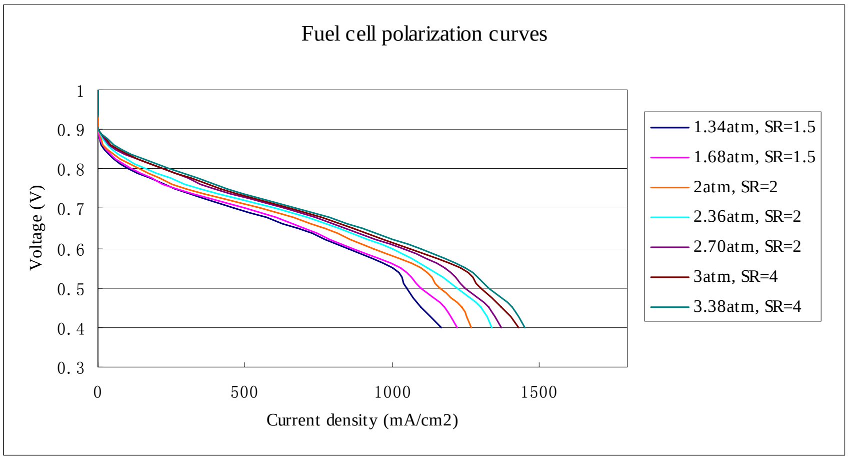


Figure 4-1 Fuel-cell V-I curves used in AVCEM

Catalyst cost is determined by the catalyst loading and the price of the platinum catalyst. The price of platinum has been volatile: it rose above US$1,000 per troy ounce after 2006, declined sharply in late 2008, and then climbed gradually to $1,200 in early 2009. This volatility, which is due to a number of unpredictable factors that affect both supply and demand, makes it difficult to estimate future platinum prices. Nevertheless, we have assumed that increased demand for platinum in the automotive sector will cause platinum prices to increase. To estimate this, we first examined the recent behavior of global platinum markets, and then employed a logistic function to model the platinum price change with global platinum demand (details will be described in Section 4.1.1). The upper limit is $2,400 per troy-ounce.

Catalyst loadings significantly affect the cost of fuel cell stack. In a recent report by the California Air Resources Board (Kalhammer et al., 2007), the total platinum loading among the FCVs in a current demonstration was between 0.8~0.9mg/cm^2. However, the US Department of Energy FreedomCAR Program (2004) has set a target of 0.2mg/cm^2 for total catalyst loading at both electrodes. Fuel cell developers estimate loadings could be as low as 0.1~0.5mg/cm^2 after 2015 without adversely affecting life and durability (Kalhammer et al., 2007). We assume that catalyst loadings decline with production volume over time, as shown in Table 4-3.

Table 4-3 Fuel cell system performance assumptions in DTI and AVCEM[a]

	Current Technology (2006)		**2010 Technology**		**2015 Technology**	
	DTI	AVCEM	DTI	AVCEM	DTI	AVCEM
System net output power	80	69.3	80	64.5	80	61.7
Power density (mW/cm^2)	700	694	1000	837	1000	989
Total Pt loading (mg/cm^2)	0.65	0.63	0.29	0.40	0.19	0.20
Anode catalyst loading	0.3	0.23	0.09	0.12	0.04	0.04
Cathode catalyst loading	0.35	0.40	0.2	0.29	0.15	0.16
Air compression	Twin Lobe Compressor, Twin Lobe Expander		Centifugal Compressor, Radial Inflow Expander		Centifugal Compressor, No Expander	
Air compressor (kW) (net of expander)	8.29	9.87	5.31	7.51	4.81	7.72

[a] Values shown under "AVCEM" are calculated by the model. We assume that the fuel cell performance improves over time.

4.1.1 Platinum price

Despite progress on alternative catalysts to platinum (Atanasoski and Dodelet, 2009, Battersby, 2009, Zelenay, 2009), current automotive fuel cells still rely upon platinum catalysts and require more than current internal combustion engine vehicles that use about 2-4 grams per vehicle in emission control equipment such as catalytic convertors. While fuel cell platinum loading has been steadily decreasing, it is likely that future mid size fuel cell vehicles (FCVs) will require 4-8 grams of platinum, assuming technical goals are met (0.1-0.19 g Pt/kW) (DTI, 2007, CARB, 2007). World platinum prices have been volatile in recent years, rising rapidly with demand, in part because of fast growing requirements for platinum for conventional vehicles. Because of the higher platinum demand per vehicle for FCVs, platinum resource constraints and rising prices are sometimes cited as a limiting factor for large market penetration of fuel cell vehicles.

We investigate the potential impact of growing platinum demand on price when worldwide hydrogen fuel cell vehicles are introduced, assuming FCVs capture major market share by 2050. We first develop a baseline trend for increased platinum demand for all users without FCVs introduction according to the recent data. Then we estimate extra automotive platinum demand from FCVs introduction and add to the baseline, which generates an alternative scenario. To model the demand-price relationship for platinum, a logistic function is proposed to fit historical data for platinum demand and price. We examine the potential impact of platinum recycling on platinum price and then set the upper price limit within about 2.0 times its current value.

4.1.1.1 Introduction

Given that the use of platinum in ICEV catalytic converters already accounts for more than one-third of total global platinum demand (source: Platinum today), a large increase in platinum demand by the automotive sector due to the widespread substitution of FCVs for ICEVs might significantly drive up platinum demand. And because the price of platinum can be especially sensitive to changes in demand, this increased demand might result in significantly higher platinum prices.

Previous researchers have recognized this issue, and have examined the relationships between platinum demand, platinum price, and total platinum cost per vehicle when large numbers of FCVs replace ICEVs (TIAX, 2003, the UK DFT, 2006, Kromer, 2009). There is some disagreement among these researchers about the impact on platinum prices of commercializing FCVs.

In 2003, TIAX (2003) completed a detailed assessment of long-term platinum supply and price for a worldwide deployment of FCVs through 2050. They analyzed two FCV scenarios: one with 50% FCV market share by 2050 and the other with 80% by 2050. They further assumed that platinum use in FCVs would decrease from 60g/FCV in 2005 to 15 g/FCV by 2025, with a 95% platinum recycling rate from fuel cells and a 90% recycling rate from ICEVs. An annual growth rate 1.4% was assumed for platinum demand in jewelry and industrial sector. They accounted for population growth in each region (US, West Europe, Japan, China and India), following United

Nations' projections. The projected annual vehicle sales in these regions reached 72 million in the 50% scenario and 93 million in the 80% scenario. The total cumulative platinum demand from 2005 to 2050 would be between 17,500 tonnes and 20,500 tonns, about one-quarter of the current (2003) world resource (76,000 tonnes, projected by TIAX). They conducted statistical tests on historical platinum prices and concluded that the real price of platinum remains stable over time because of steady increases in supply. Based on this finding, econometric models were developed for platinum supply and demand. Their analysis concluded that platinum price would increase in the short run by up to 30%, due to increased demand, but that gradually the supply of platinum from primary production and recycling would increase and cause the price of platinum to gradually decline to its long-term mean price of $550/troz (the average of historical real prices 1880-1998). However, for the 80% scenario, TIAX concluded that the platinum demand growth rate "could exceed the expansion capabilities of the industry." (p.20) However, TIAX conducted this study in 2003 when the price of platinum was relatively low, less than $800/troy-ounce, and their conclusions about the response of the platinum industry might not apply today, when platinum prices are much higher. Platinum supply cost and current low platinum recovery rate are not discussed in the TIAX study.

The Department for Transport (DFT) in the UK (2006) developed a simple model to explore the likely impact of hydrogen FCVs on platinum demand for the years 2000, 2010, 2020, 2030, 2040 and 2050. Their analysis is based on several assumptions:

platinum demand from non-automotive applications is constant at 2000 levels; total global car sales would increase at a rate of 45% per decade from 2000; platinum loadings for autocatalysts are constant (1.4 grams per car); platinum loadings for fuel cell would decrease from 56.7 grams per car in 2000 to 5.7 grams for 2030 and beyond; cars have a lifetime of 10 years; platinum recovery rate from autocatalysts is 90% and the recovery rate from fuel cells is 95%. Three scenarios ("slow", "rapid" and "unrealistic growth") are assumed for market penetration of fuel cell cars. This study suggests that "platinum availability should not be a constraint to the introduction of hydrogen fuel cell cars" if South Africa can increase platinum production by 5% every year. However, the DFT study does not address the impact of increasing platinum demand on platinum price.

In a recent study by TIAX LLC and US DOE (Kromer, 2009), an evaluation of the feasibility of a platinum leasing program for future fuel-cell vehicles in the United States shows that platinum leasing would reduce the upfront price of platinum charged to the consumer by up to 40%, depending on the current market platinum price, platinum loading, lender's lease rate, borrower's discount rate and vehicle lifetime. With a platinum leasing program, an upstream lender (a fuel cell supplier or a catalyst fabricator or a bank) or downstream lender (a bank or an automotive financing company) leases the platinum to the OEM or the consumer at a lower price than if platinum is not leased. When the vehicle retires, "the FCV owner would need to return the vehicle to an established FCV reclaimer, who would then pay the lender for the assayed value of the platinum in the vehicle." The lease rate is set by the lender to make the return with risk adjustment cover all the costs (finance, overhead, and any difference between the initial purchase price and the final recovered value of platinum). The cost savings to consumer are quite sensitive to the lease rate. Separate ownership of the platinum and the vehicle shifts a portion of total platinum cost from consumer to supplier or other organization, which could largely improve the recovery rate of platinum for FCVs. The lease program may facilitate FCVs market penetration especially in the early stages by internalizing the residual value of platinum in the vehicle cost.

Finally, unlike the above studies, Yang (2009) stressed that insufficient platinum supply and expensive platinum would be a barrier to widespread commercialization of hydrogen FCVs based on his analysis of platinum demand and supply.

We build on prior work with an integrated analysis of FCV market growth, platinum loading per vehicle, platinum demand, platinum price as a function of demand, and platinum cost per vehicle. Our ultimate objective is to estimate the total platinum cost per FCV, which (at the manufacturing cost level) is simply the product of the platinum used per FCV and the price of platinum. We estimate the platinum used per FCV as a function of the number of vehicles produced each year, assuming that the platinum loading declines as technology improves with production. We estimate the price of platinum formally as a function of the demand for platinum, with an informal consideration of the effects of recycling. The demand for platinum, in turn, is a function of the amount of platinum per FCV and the total number of FCVs. We estimate the total number of FCVs on the road with a fleet turnover model, which allows us to derive the recycled platinum supply and then examine the change of platinum price with large-scale FCV introduction.

In the first step of the analysis, we estimate the global demand for platinum with large penetration of FCVs. The global demand is equal to a baseline demand, comprising demand from a global fleet of ICEVs and demand from non-automotive uses, plus additional demand due to FCV introduction. In the baseline, the total platinum demand increases by 35% by 2020 and by 131% by 2050 over the level in 2009. The extra automotive platinum demand from FCV introduction is equal to the difference in platinum requirement between a FCV and a conventional vehicle (which declines over time as more FCVs are produced) multiplied by the number of FCVs sold that year. We use a fleet turnover model to estimate FCV penetration over time. In our main scenario, we assume that FCVs are introduced in increasing numbers until they capture 40% of global light-duty vehicle (LDV) sales by 2050. For platinum supply, we consider different platinum recovery rates for ICEVs and FCVs, and estimate virgin platinum supply each year with the fleet turnover model.

In the second step of the analysis, we formulate the price of platinum as a logistic function of the total demand for platinum, with assumed upper and lower limits on the price. We estimate coefficients for this function so that the resulting price-vs.-demand curve has a plausible shape and fits historical data. We estimate the upper limit of platinum price on the basis of a qualitative consideration of the prospects for recycling and of other factors that affect long-run platinum supply.

Finally, we examine how platinum cost of fuel cells is likely to change with increasing production as platinum demand and price increase but platinum loading decreases. With a single unified model, we estimate how both the price of platinum and the platinum loading per vehicle change with increasing production of FCVs. We report the total platinum cost, the platinum cost as a fraction of fuel-cell and vehicle cost, and some demand/cost elasticity measures, which show the % change in fuel cell cost or vehicle cost for some % increase in platinum price and some % increase in FCV penetration.

Our work expands upon previous research in several ways. We develop a scenario of global platinum demand with large penetration of FCVs that takes into account declining platinum loadings per FCV. Considering several factors that affect platinum price, we assume a logistic function to relate platinum price to platinum demand and then estimate how the manufacturing costs of fuel cells and FCVs would change with increasing platinum demand and price. Our study has a single, unified treatment of FCV introduction, platinum demand, platinum loading, and platinum price.

4.1.1.2 Platinum demand scenarios

In this section, we establish the platinum demand scenarios we will use in the estimation of platinum price. As mentioned above, we estimate the price of platinum formally as a function of platinum demand, with informal consideration of the impact of platinum recycling on price. To inform this qualitative treatment of the relationship between platinum recycling and platinum price, we include a separate accounting of platinum recycling in the fleet turnover model we use to estimate platinum demand by the automobile sector. (Section 4.1.1.3 provides details on our informal consideration of the price effects of platinum recycling.)

For our discussions of platinum demand and price, we define three terms:

Platinum demand over a period of time is the total amount of platinum in goods newly produced over that period. It also can be understood as total platinum use, total platinum consumption, or total platinum quantity supplied.

Virgin platinum supply is the portion of the platinum demand that is supplied by platinum produced from raw (“virgin”) ore.

Recycled platinum supply is the portion of platinum demand that is supplied by platinum that is recycled from end-use goods or manufacturing scrap.

These three terms satisfy the following equality:

platinum demand = virgin platinum supply + recycled platinum supply.

The first step here is to estimate baseline annual platinum demand with no FCVs. Platinum is used in autocatalysts, jewelry, investment and industrial applications. We estimate platinum demand by auto sector and other sectors (jewelry, industrial application, and investment) separately. Figure 4-2 shows historical platinum demand by autocatalysts and other (non-auto) sectors (source: Platinum today). Annual platinum demand by other sectors has been relatively stable, in the range of 110-130 tonnes, while annual platinum demand by autocatalysts generally has increased over time. To project the platinum demand by other sectors beyond 2009, we simply fit a straight line to the recent data from 2003 to 2009. The projected platinum demand by other sectors ranges from 117 to 135 tonnes over the period 2010-2050 as shown in Figure 4-3.

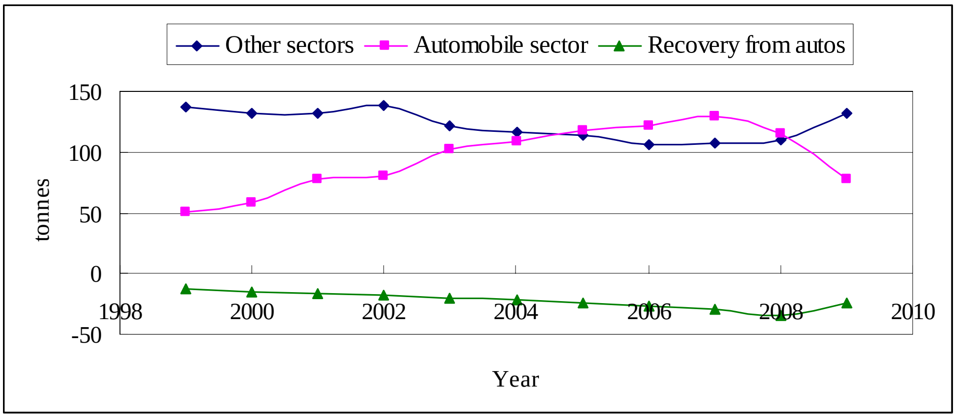


Figure 4-2 Platinum demand 1998-2009

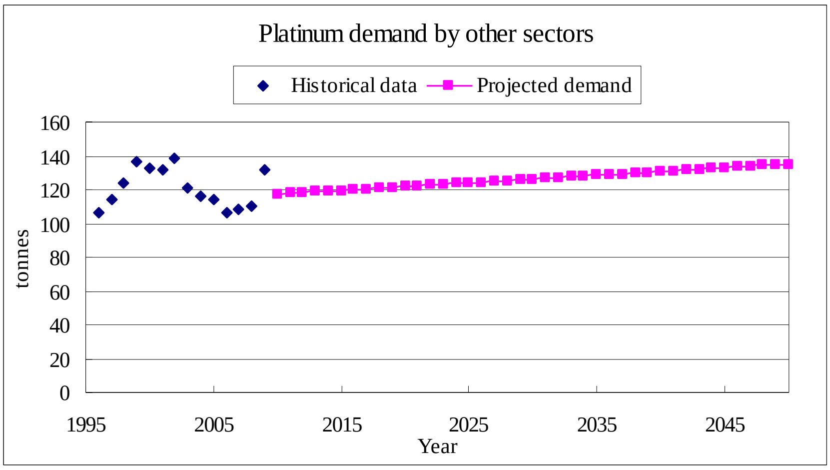


Figure 4-3 Platinum demand by other (non-auto) sectors

For auto demand for platinum in the baseline, we assume that all LDV sales from 2010 to 2050 are ICEVs under the BLUE Map scenario from the International Energy Agency (IEA) Energy Technology Perspectives Report (ETP 2008) as shown in Figure 4-4. We assume that over the entire period the average platinum used in each new LDV will equal the average in 2008, which was 118.3 tonnes of platinum in automobiles globally divided by total global LDV sales in 2008 of 60 million (ETP 2008), or about 2 grams per new ICEV. With these assumptions, we develop the baseline platinum demand for autocatalysts as shown in Figure 4-5, assuming no FCVs are introduced. The total global platinum demand increases from 240 tonnes in 2009 to 280 tonnes by 2020 and 480 tonnes by 2050.

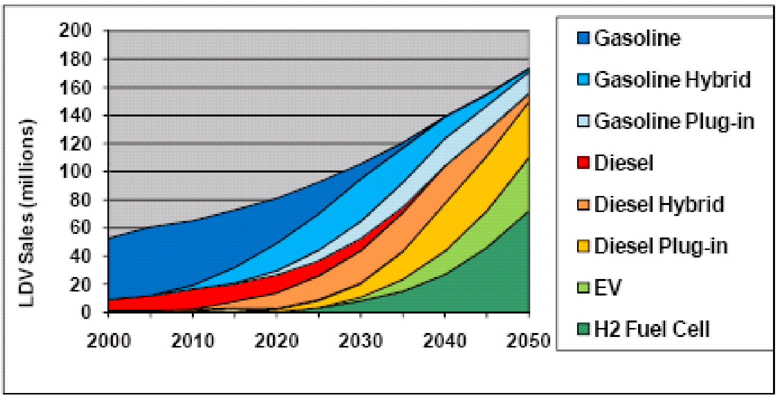


Figure 4-4 Global LDV sales in ETP BLUE Map (ETP, 2008)

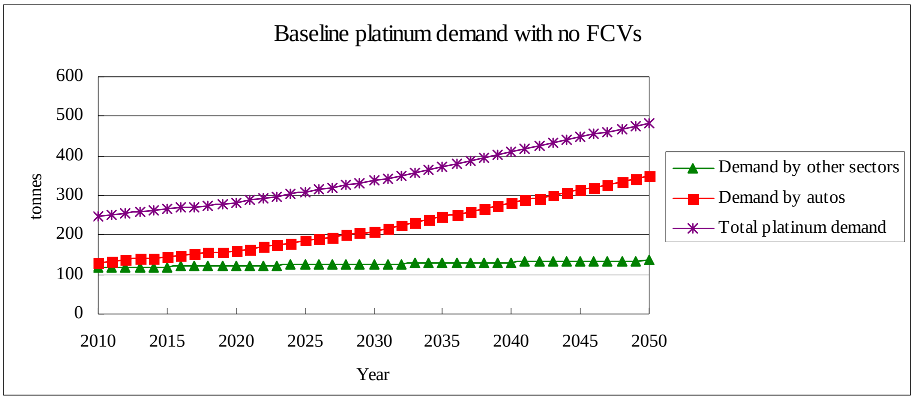


Figure 4-5 Our projection of platinum demand in the no-FCVs baseline

In the next step, we project platinum demand in the FCV scenario of the ETP BLUE Map as shown in Figure 3. We model platinum loading per FCV as a function of annual FCV production, and then project the total platinum demand.

The platinum loading per FCV can be calculated as the product of the fuel cell power and the platinum content per kW of power. According to the US Department of Energy (James and Kalinoski, 2007), the 2015 target value for total platinum catalyst loading for automotive fuel cells is 0.19 grams per kilowatt of fuel cell output power. Another report by the California Air Resources Board (2007) found a lower bound of 0.1 milligram/cm^2 in 2015 and beyond, which, given a future fuel cell areal power density of 1 watt/cm^2, corresponds to 0.1 g Pt/kW. We assume a range of 0.1 to 0.2 g-Pt/kW for future FCVs. Assuming that it will be most economical to supplement fuel cells with a peak-power battery (Kromer, 2007), and then the power of the fuel cell will be relatively modest – perhaps about 40 kW. With these assumptions, the platinum requirements for future FCVs in high production volumes would be 4-8 grams per vehicle. However, a current fuel cell car contains more platinum. According to TIAX (2003) and UK DFT (2006), platinum loading per car in 2005 is about 55-60 grams for a 75kW fuel cell system. We estimate the platinum loading *L* per FCV as a function of annual FCV production (Q) with a lower limit of 6g/car, as shown in equation 4-1, which is calibrated with two assumed data points[3]. Figure 4-6 presents how the platinum loading per FCV declines over time, according to equation 4-1, with Q, the annual production volume based on the ETP BLUE map scenario (Figure 4-4).

$$L = a \cdot Q^b \text{, if } L \geq 6 \text{, otherwise } L = 6 \qquad (4\text{-}1)$$

Where *a=658* and *b=-0.29* are coefficients.

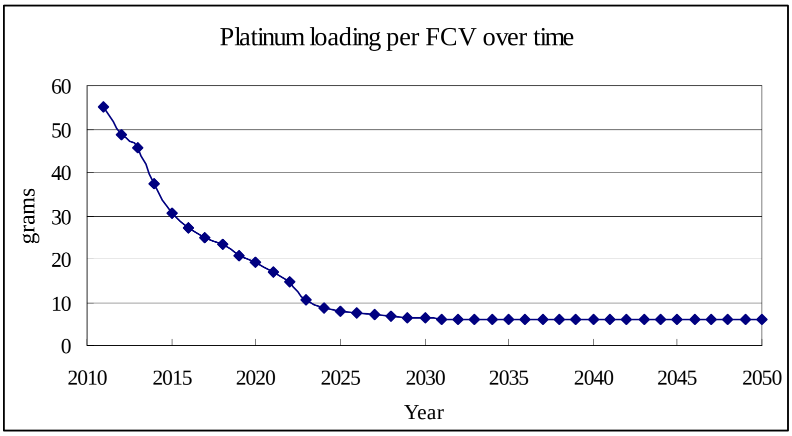


Figure 4-6 Platinum loading per FCV

[3] We assume that globally there are 5,000 units of FCVs produced in 2010 and 10,000,000 units in 2025 and platinum loading per FCV will decrease from 55g in 2010 to 6g in 2025 and beyond.

The BLUE Map scenario assumes an optimistic mix of new technologies for the transport sector, “a combination of high efficiency, biofuels, electric vehicles and hydrogen fuel cell vehicles” in which FCVs reach 40% of LDV sales globally by 2050. These FCVs, replacing conventional vehicles in the LDV fleet, require extra platinum per vehicle, which is then added to the baseline scenario. Assuming 2g per ICEV and the declining platinum loading per FCV shown in Figure 4-6, we estimate the total platinum demand from autos (ICEVs plus FCVs) and other sectors for our FCVs scenario. As shown in Figure 4-7, the total platinum demand will be around 680 tonnes by 2050, about 200 tonnes more than in our baseline without FCVs. The demand for FCVs increases sharply beyond 2020 as production volume increases while the demand for ICEVs increases at a very low rate (because it is dampened by expanding demand for FCVs) and starts to decline in 2040.

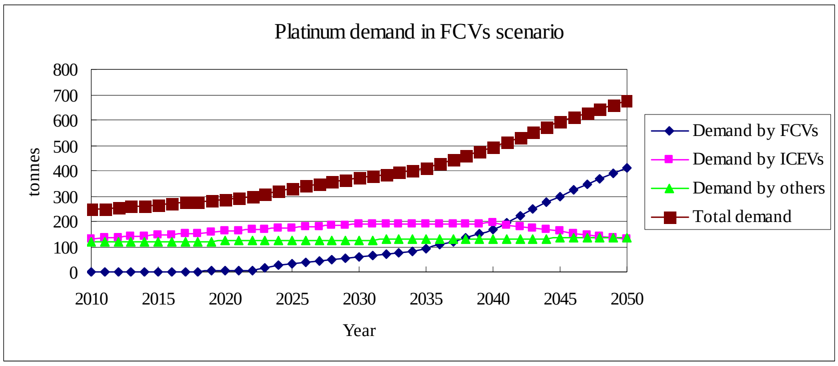


Figure 4-7 Platinum demand in the FCVs scenario

The total platinum demand is met by a combination of recycled platinum (from scrapped cars) and virgin platinum. To model the amount of platinum available from recycling, we assume different platinum recovery rates for ICEVs and FCVs, and calculate recycled platinum supply with the vehicle fleet turnover model.

To derive annual virgin platinum supply, we need to estimate platinum recovery from autocatalysts and fuel cells. In recent years, annual platinum recovery from autocatalysts accounts for more than 30% of annual demand by autocatalysts (where recovery and demand are measured in the same year). We define platinum recovery rate (PRR) as the ratio of recycled platinum from a retired ICEV or FCV to total platinum contained in the ICEV or FCV in the year of vehicle production. Hagelüken notes that the recovery rate of PGMs from autocatalysts on a global level is only about 50%, primarily because of a lack of appropriate end-of-life management (Hagel üken , 2007). We assume the current PRR (year 2010) is 0.5 for both ICEVs and FCVs, and the PRR will increase at an annual rate of 1.5% to a maximum of 0.9 for ICEVs and at an annual rate of 2% to a maximum of 0.95 for FCVs.

To estimate the FCV stock over time, we use a fleet-turnover model calibrated to produce results consistent with the IEA BLUE Map Scenario (Figure 4-4). Our estimate shows that the global FCV stock would be around 631 million in 2050 when the global FCV sales reach 68.8 million. With the vehicle fleet turnover model that enables tracing the production year of retired FCVs, we calculate the annual amount of platinum in retired FCVs available for recovery, which is multiplied by the corresponding PRR to produce annual recycled platinum from FCVs. For example, if two FCVs retire in 2025 (one produced in 2012 with 48g platinum and the other in 2015 with 30g platinum), and PRR in 2025 is 67%, the recycled platinum from these two FCVs would be (48+30) x 67%=52g.

We use the same method to estimate the annual recycled platinum supply from ICEVs. The recycled platinum from ICEVs in 2050 would be 165 tonnes. Adding up the recycled platinum from FCVs and ICEVs provides total recycled platinum supply per year, as shown in Figure 4-8. We then subtract the recycled platinum supply from total platinum demand (the dark red curve in Figure 4-7) to produce virgin platinum supply, shown as the green curve in Figure 4-9. The increasing PRR increases recycled platinum supply, which dampens the increase in virgin platinum supply. Virgin platinum supply beyond 2035 would remain relatively stable, about 300 tonnes, roughly 1.5 times the 2009 level. In the next section, we discuss how these trajectories might affect prices.

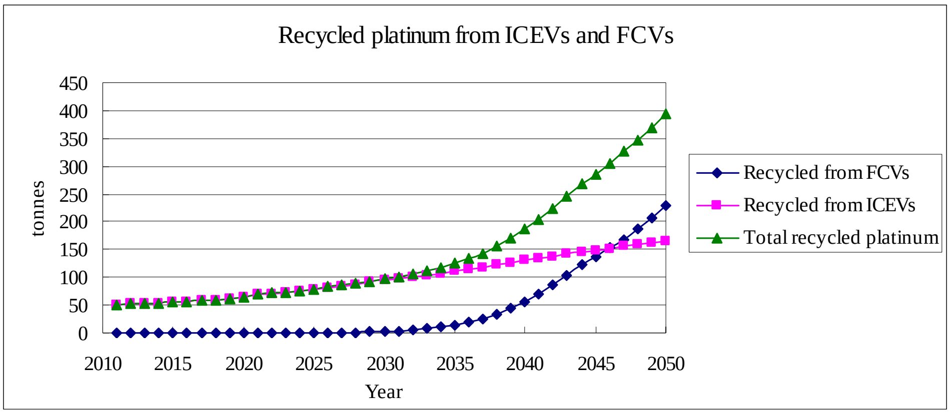


Figure 4-8 Projected total recycled platinum supply from FCVs and ICEVs

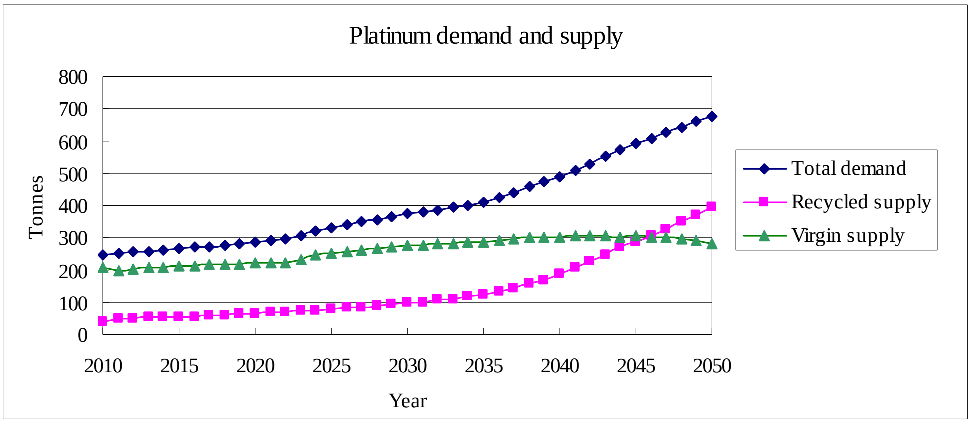


Figure 4-9 Projected annual platinum demand, recycled platinum supply and virgin platinum supply, given FCV penetration calibrated to IEA "BLUE Map" projection for 2050, and declining platinum loadings per FCV

4.1.1.3 Platinum price as a function of demand

To estimate how the price of platinum changes with demand, we assume a simple logistic function, for which platinum price versus demand is an S-shaped curve lying between a lower price limit and an upper price limit (eq. 4-2):

$$\frac{P - P_L}{P_U - P_L} = \frac{1}{1 + \exp(-c_1 - c_2 \cdot D)} \qquad (4\text{-}2)$$

where P_L is the lower limit of platinum price, assumed to be \$400/troy-oz based on the historical data; P_U is the upper limit of platinum price, which we estimate as a multiple of the current price of approximately \$1500 per troy ounce; D is annual platinum demand (tonnes); and c_1 and c_2 are coefficients.

We estimate coefficients c_1 and c_2 to provide the best fit to the historical data over the period 1993-2009 (Table 4-4). Both coefficients are statistically significant and the logistic function is a good fit (R-squared=0.73). As shown in Figure 4-10, our function captures the general trend over the period 1993-2007, but the estimated values for the years 2008-2009 are much lower than actual values.

Table 4-4 Logistic estimates

Variable	Coefficient	Standard Error	T Stat	P-Value
C_1	-8.82362	1.15826	-7.618	<0.00001 ***
C_2	0.0310180	0.00563948	5.500	0.00006 ***
Unadjusted R-squared = 0.730553				

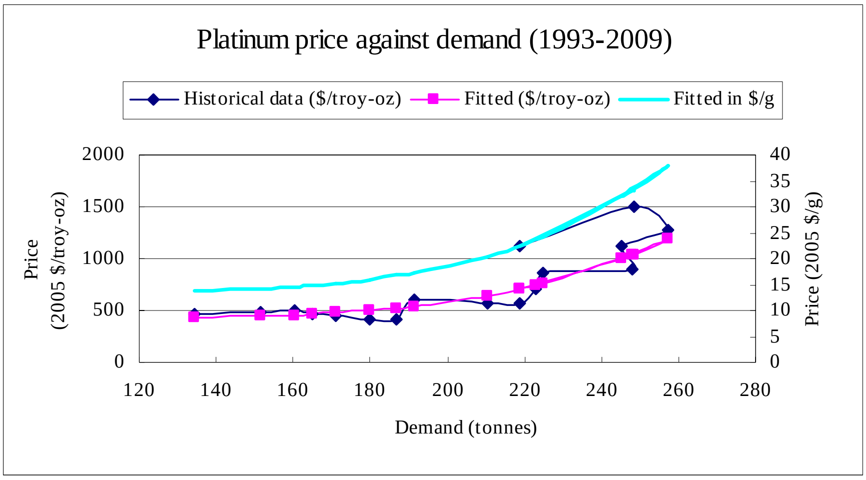


Figure 4-10 Platinum price versus annual platinum demand

We assume this functional form because we believe that initially greater demand will increase the price of platinum but that in the long run increased recycling (and increased use of substitutes) will dampen and eventually flatten the price trajectory. In support of this, we can (in three steps) transform the green curve in Figure 4-9 into a notional platinum price-vs.-demand curve, which will turn out to be S-shaped (logistic). First, note that the virgin-platinum supply curve in Figure 4-9 can be described by a relatively flat logistic function with a lower limit of 199 tonnes per year and an upper limit of 307 tonnes per year. Next, transform the horizontal axis of this curve from years to the associated annual platinum demand. The resulting curve of virgin platinum supply versus platinum demand also is logistic, with the same upper and lower limits of virgin platinum supply. Finally, assuming that the price of platinum is determined by the cost of virgin platinum, and assuming that the $/troy-oz cost of virgin platinum always increases with the supply of virgin platinum (eq. 4-3 and Figure 4-11), we can transform virgin platinum supply versus platinum demand into platinum price versus platinum demand by reading off the associated supply cost from virgin platinum supply curve. This final transformation also will result in a logistic function with upper and lower limits, but with a "steeper" rise than in the virgin-platinum-supply-versus-platinum-demand curve, as shown in Figure 4-12 (The rise will be steeper because the $/g platinum cost increases with increasing virgin platinum supply.) The virgin-platinum cost function is given by:

$$MC = \exp[k_1 + k_2 \cdot \ln(S)] \qquad (4\text{-}3)$$

where MC is the marginal cost of virgin platinum supply and S refers to platinum supply. We use the log-linear functional form to fit historical price and supply data 1993-2009 (Figure 4-11) and assume platinum price equals MC.

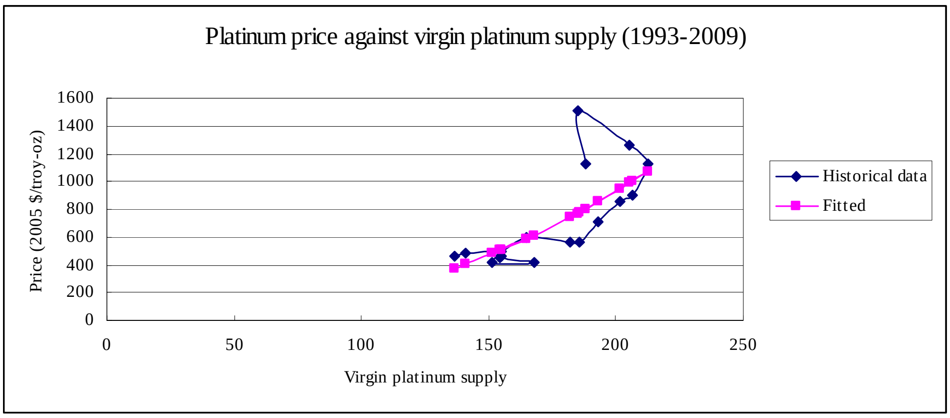


Figure 4-11 Virgin platinum supply cost curve

The three-step transformation generates the platinum-price-against-annual-demand curve with a lower limit of about $1,100/troy-oz and an upper limit of about $2,600/troy-oz for the FCVs scenario (Figure 4-12). When annual platinum demand exceeds 600 tonnes, the price of platinum would approach the upper limit.

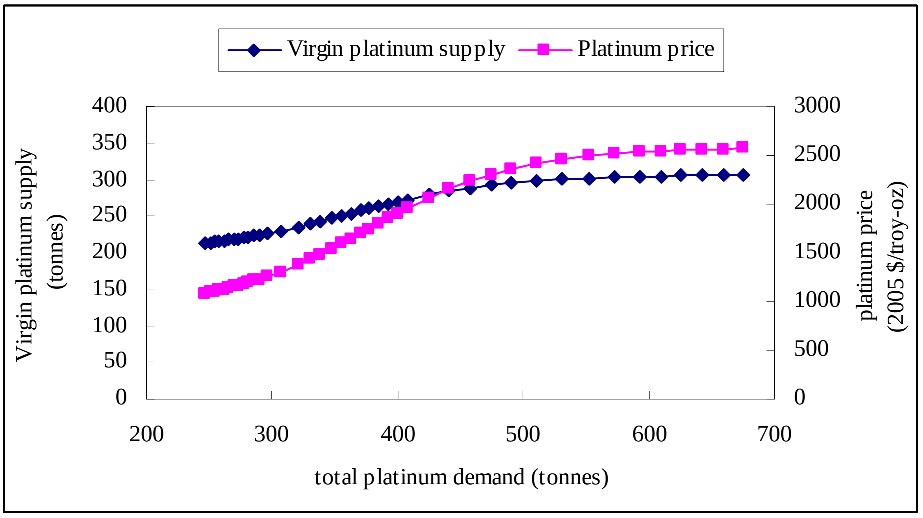


Figure 4-12 Virgin platinum supply and platinum price versus platinum demand, transformed from the virgin supply curve (the green one in Figure 8) assuming a logistic function

This exercise suggests that the upper limit of platinum price – *Pu* in eq. 4-2 – should be at least $2,600/troy-oz. However, this particular result depends on the virgin platinum supply function (eq. 4-3), which could be different than we have estimated. Moreover, the upper limit Pu could be determined by other factors as well. Therefore, in the next section we examine this question of the upper limit in more detail.

4.1.1.4 Qualitative discussion of upper limit of platinum price

To provide a basis for an estimate of the upper limit on platinum price (P_U in eq. 4-2), beyond what is suggested by Figure 4-12, we discuss historical price trends, future platinum demand relative to platinum reserves, and factors that determine the shape of the long-run supply curve. We examine the prospects for recycling and substitutes for platinum in some detail, because both of these at some point will limit the demand for and hence cost of virgin platinum, which as mentioned above determines the market price of platinum.

Recent trend shows that the price of platinum has generally been increasing since the year 2000 due to faster growth of demand than supply. However, it is uncertain whether the price will continue to rise because of a number of supply and demand-side affecting forces. In 2008, platinum price per troy-oz started at $1,530 in January, climbed to $2,276 in March and ended at $899 in December. High price was driven by supply disruption (electricity supply problems in South Africa) and strong investor interest in the first half of 2008 (Jollie, 2009). Platinum price began to drop in July 2008 largely because of global economic downturn. In the future, the platinum price will depend upon the outlook for the automotive industry, demand from jewelry sector and investment sector, and expansion capabilities of major suppliers (Loferski, 2010).

Platinum supply has been inelastic due to constraints on producers' sociopolitical environment and infrastructure (Yang, 2009). South Africa, the world's largest supplier of PGM, provides about 80% of the world's PGM. Producers face supply expansion challenges such as restricted electrical power supply, limited and shrinking skills pool and increasing capital and operating costs (Williams, 2008). Platinum demand also has been inelastic because few substitutes are available. Theoretically, this inelasticity will result in a sharp increase in price when demand expands, at least in the short run. TIAX's (2003) econometric model of platinum price and demand supports this, indicating that platinum price will increase in the short-run in response to demand increase from FCVs. However, TIAX assumes that platinum production can be increased at relatively low cost, so that eventually the platinum price is expected to return to its long-term mean price because increased production restores balance between supply and demand. It is not clear to us if this assumption is valid, especially in the face of large increases in demand such as we consider here.

There are at least five factors that determine whether the long-run supply curve for platinum is relatively flat, as TIAX assumes, or instead is upward sloping: 1) the major supply countries' production capacity in response to large changes in demand; 2) the economically available reserves relative to total production; 3) the recycling rate; 4) the recycling cost at a large scale, and 5) the possibility of alternative non-precious catalysts. Although the first two could be barriers to FCVs commercialization due to short-term production constraints in South Africa, the world's largest supplier for platinum group metals (Yang, 2009), these supply-side problems dot not seem permanent According to a study by Spiegel (2004), the International Platinum Association concludes that “there are sufficient accessible reserves to increase supplies by up to 5-6% per year for the next 50 years.”

USGS (2010) estimates PGMs reserves that could be economically extracted or produced in 2009 are 71,000 tonnes. TIAX (2003) projects about 76,000 tonnes for world platinum resources. According to our estimate for platinum demand shown in Figure 4-9, the cumulative platinum demand from 2010 to 2050 is about 16,500 tonnes, less than 25% of the world platinum resources. Thus, resource availability would not be a limiting factor to meet platinum demand for large penetration of FCVs by 2050, although eventually, after many more decades, it could be a limiting factor.

The impact of recycling on long-run platinum supply costs depends on the cost of recycling relative to the cost of virgin platinum supply, and the extent of recycling. The full recycling costs for platinum (logistic, dismantling and refining costs) in a large-scale, international recycling system will remain much less than the cost of producing virgin platinum metal (C. Hagelüken, Umicore, personal communication, Sep. 2009). According to Hagelüken, the current sampling and refining costs for car catalysts are only about 10% of the intrinsic metal value, and although the costs for platinum recovery from fuel cells will be higher because fuel cells are more complex and special emission control is needed, they still will be significantly lower than the platinum price and the cost of virgin platinum.

According to Hagelüken et al. (2009), recycling rates would be increased by a progressive conversion of existing open loop recycling systems into more efficient closed (direct) loop systems that typically recover and recycle more than 90% of the Platinum group metals (PGMs) used in industrial processes. Spiegel (2004) assumes that 98% of the platinum in FCVs will be recoverable in his analysis of the impact of FCV platinum on world platinum production. Our simulation has shown that a high PRR will lead to less production of high-cost virgin material, which will ease pressure on the price of platinum. However, the extent of recycling at a global scale is uncertain because a global recycling system requires international agreement on standards, protocols, infrastructure, management and enforcement (C. Hagelüken, Umicore, personal communication, Sep. 2009).

The final factor to consider is the possibility of developing low-cast, non-precious metal catalysts. Recent work suggests that alternative catalysts based on inexpensive, abundant materials may be available relatively soon. Non-Platinum Bimetallic Cathode Electrocatalysts replace some PGMs with base metals and thereby reduce total catalyst cost (Myers, 2009). A report on iron-based catalysts (Lefèvre, 2009) shows that microporous carbon-supported iron-based catalysts can produce the current density of a cathode equal to that of a platinum-based cathode with a loading of 0.4 mg/cm^2. These studies suggest that a world-wide FCV market will not have to reply on precious-metal catalysts indefinitely. The use of lower-cost substitutes, like the use of recycled platinum, will displace virgin platinum supply and dampen the increase in price.

Considering all these factors, we assume that when the price of platinum is twice the current (year-2010) price (about $1500 per troy ounce), the availability of recycling and non-precious-metal alternatives will prevent further increases in the price of platinum. This assumption that P_U (eq. 4-2) = $3,000/troy-oz is roughly consistent with the upper limit of $2,600/troy-oz in Figure 4-12.

It is worthy noting that our results are very sensitive to our input assumptions. If platinum loading per FCV doesn't meet its goal (6g/FCV) and remains at 15g/FCV beyond 2021, the demand for virgin platinum could reach nearly 600 metric tons by 2050, which is three times the current platinum supply. In this case, the platinum price would be relatively high if major suppliers were not able to expand their production. Similarly, if platinum loading meets its goal but platinum recycling rate remains at 50%, the demand for virgin platinum again will continue rising beyond 2050.

4.1.2 Fuel cell system cost model

Fuel cell system includes fuel cell stack and balance of plant (BOP). The fuel cell stack contains membrane, gas diffusion layer (GDL), electrodes with catalyst, bipolar plate and other materials such as gasket, endplates and so on. The balance of plant comprises auxiliary subsystems: air management, water management, thermal management and fuel management.

The total fuel cell system cost C_{sys} ($ per kW of stack peak power) is calculated in AVCEM as follows:

$$C_{sys} = (C_m + C_{GDL} + C_E + C_{Pt} + C_B + C_o) / p_{den} + (C_a + C_w + C_t + C_f + C_{so}) / P_m + C_{ska} / P_m + C_{sysa} / P_m, \quad (4\text{-}4)$$

$C_{Pt} = P_{Pt} / 31.104 * L_{Pt} * 10$ and $p_{den} = V * I / 100$.

where C_m is the membrane cost ($/m^2), C_{GDL} the GDL cost ($/m^2), C_E the electrode cost ($/m^2), C_{Pt} the platinum catalyst loading cost ($/m^2), P_{Pt} the platinum price ($/troy-oz), L_{Pt} the total platinum loading (mg/cm^2), C_B the bipolar plate cost ($/m^2), C_o the other materials cost ($/m^2), p_{den} the power density (kW/m^2), V the cell voltage (V), I the current density (mA/cm^2), C_a the air management system cost ($), C_w the water management system cost ($), C_t the thermal management system cost ($), C_f the fuel management system cost ($), C_{so} the system controller and other cost ($), P_m the stack peak power (kW), C_{ska} the stack assembly cost ($), and C_{sysa} the system assembly cost ($).

To estimate how fuel cell system cost change over time, we employ a learning curve characterized by three factors, as shown in Equation 4-5 for each cost item in Equation 4-4 except platinum, in conjunction with three scenarios of FCVs introduction from the U.S. Department of Energy (DOE) (Gronich, 2007), shown in Figure 4-13. We assume the platinum catalyst loading on anode and cathode is dependent on time (t) only, as shown in Equations 4-6 and 4-7.

$$C(t,Q,N) = C(LR) * A(t) * S(Q) * L(N) \quad (4\text{-}5)$$

$$L_{Pt\_a} = \exp(a_1 * (t - t_0) + b_1) \quad (4\text{-}6)$$

$$L_{Pt\_c} = \exp(a_2 * (t - t_0) + b_2) \quad (4\text{-}7)$$

Where $C(LR)$ is the long-run OEM cost per unit, t is time (year), Q is annual production, and N is cumulative production. We use the detailed cost data points from DTI to calibrate these factors for each fuel cell component. The technological advances in Table 4-3 are assumed to be implemented in mass production of fuel cell systems five years later than DTI's assumptions. The three learning-curve factors, A(t), S(Q), and L(N), are estimated as follows:

$A(t) = \exp\{a * (t - t_0) + b\}$ for $t < t_0$, otherwise $A(t) = 1$, t_0 is the base year, and a and b are parameters;

$S(Q) = \exp\left(\ln\left(\frac{Q}{Q_0}\right)^c + d\right)$ for $Q < Q_0$, otherwise $S(Q) = 1$, Q_0 is the base annual production, and c and d are parameters;

$L(N) = \left(\frac{N}{N_0}\right)^{\log_2(1-lr)}$ for $N < N_0$, otherwise $L(N) = 1$, N_0 is the base cumulative production, and lr = learning rate. According to a study (IEA, 2000) by Internal Energy Agency, the distribution of learning rates from 108 observed cases in manufacturing firms shows that the most probable value is 18%. We assume higher learning rates (10-20%) for membrane, GDL, bipolar plate, electrode and stack assembly, and relatively low learning rate (about 5%) for the rest of the fuel cell system.

L_{Pt_a} and L_{Pt_c} are the catalyst loading on anode and cathode respectively, t_0 is the base year, and a_1, a_2, b_1 and b_2 are parameters to be calibrated with data from DTI. The lower limit is set for L_{Pt_a} (0.01 mg/cm^2) and L_{Pt_c} (0.09 mg/cm^2) to ensure the total loading no more than 0.1 mg/cm^2 (Kalhammer et al., 2007).

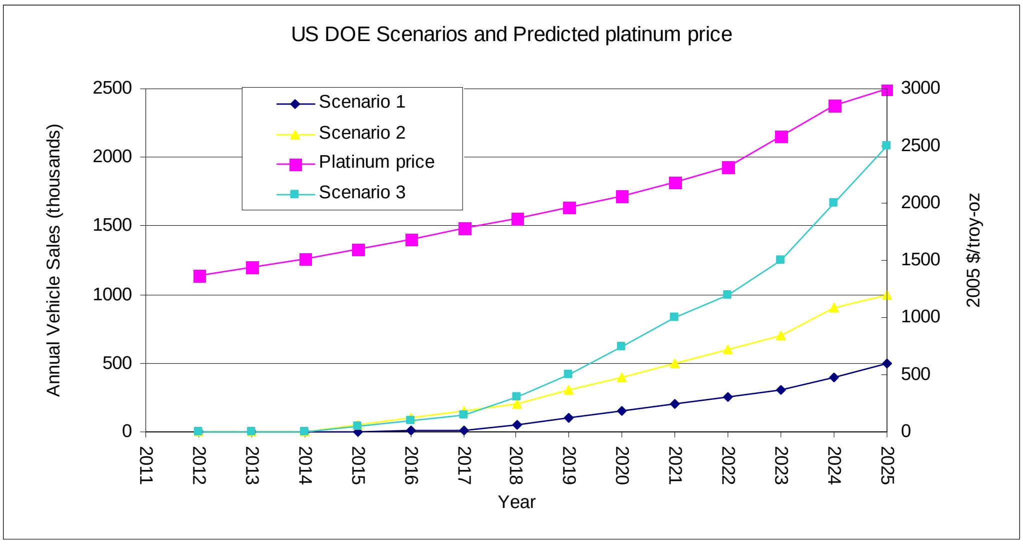


Figure 4-13 Three US DOE FCVs introduction scenarios

Platinum price is obtained from eq. 4-2 and Figure 4-9 (total demand in dark blue) with the upper limit of $3,000/troy-oz, in the range of about $1,137 and $2,503 per troy-oz over the period from 2012 to 2025, as shown in Figure 4-13. Figure 4-14 shows our estimated fuel cell system cost reduction over time with different learning rates under the US DOE scenario 3. The system cost is several thousand US dollars per kW initially and then decreases dramatically as production volume increases, especially in the first three years. Eventually, each factor declines to 1 and the “learned-out” fuel cell system cost in 2025 is about $60/kW that is much higher than the DOE targets ($45/kW by 2010 and $30/kW by 2015).

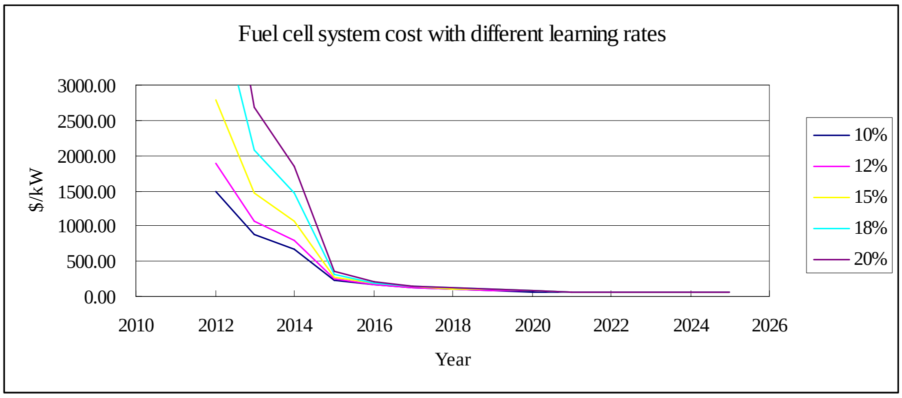


Figure 4-14 Our estimated fuel cell system ($/kW) under scenario 3

According to some studies on fuel cell cost estimates (Lipman, 1999, Tsuchiya, 2004, Schoots, 2010), currently fuel cell system cost is in the range of $1,500 and $2,000 per kW. Thus our estimate based on the data from DTI using 12% of learning rate seems reasonable. We use this cost curve to examine the potential impact of platinum price on costs of fuel cell system and hydrogen FCV. Note that we use a composite learning curve model to estimate fuel cell system cost and some learning effects are represented by technological progress and economies of scale. Hence, the learning rate of 12% is lower than that (around 20%) used in most fuel cell cost studies where learning is assumed to be the only cost reduction mechanism.

Figure 4-15 presents our estimated fuel cell system cost change over time for the three U.S. DOE Scenarios (shown in Figure 4-13). Under scenario 3 when cumulative production volume is about 10 million in 2025, the fuel cell system cost (stack and BOP) is about $60 per peak kW stack power output. Further system cost reduction would depend on technology advances on materials, power density, catalyst loadings improvements, and simplification of BOP. The estimated fuel cell system cost is considerably higher than the DOE targets ($45/kW by 2010 and $30/kW by 2015), but is consistent with DTI's estimate that at an annual production rate of 500,000 in 2015 a fuel-cell system would cost $59/kW (James, 2007).

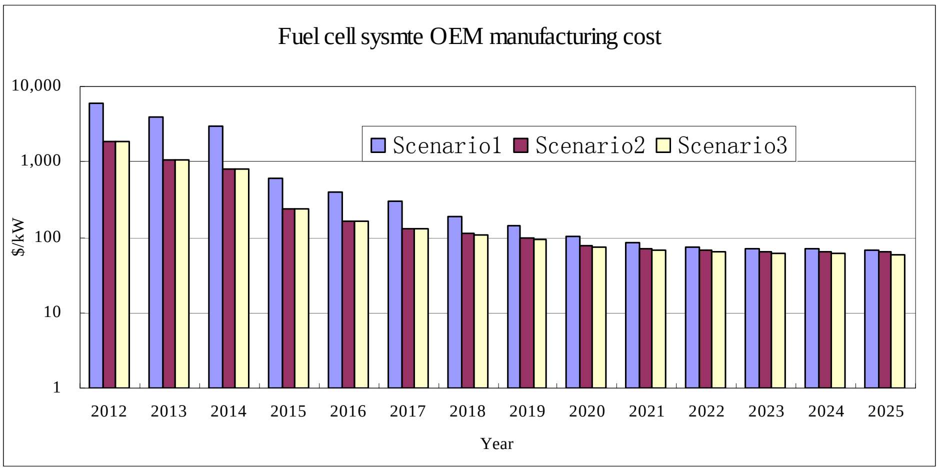


Figure 4-15 Our estimated fuel cell system cost for the three FCV introduction scenarios as shown in Figure 4-10

Figure 4-16 shows the cost breakdown for fuel cell stack: each component cost declines over time as technology improves and scale of production increases. Although the platinum price increases between 2012 and 2025, the catalyst cost declines from $21/kW in 2015 to about $8/kW in 2025 because of decreasing catalyst loading and increasing fuel cell power density, as well as scale economies of mass production. This is different from DTI's result (2007) from $45/kW at 30,000/year in 2006 to $8.4/kW in 2015 where catalyst price was constant at $1,175/troy-oz. Particularly, catalyst cost as a fraction of fuel cell stack cost increases from 2% in 2012 to 34% in 2025 because of increase in platinum price and great cost reductions of other components as a result of learning effect.

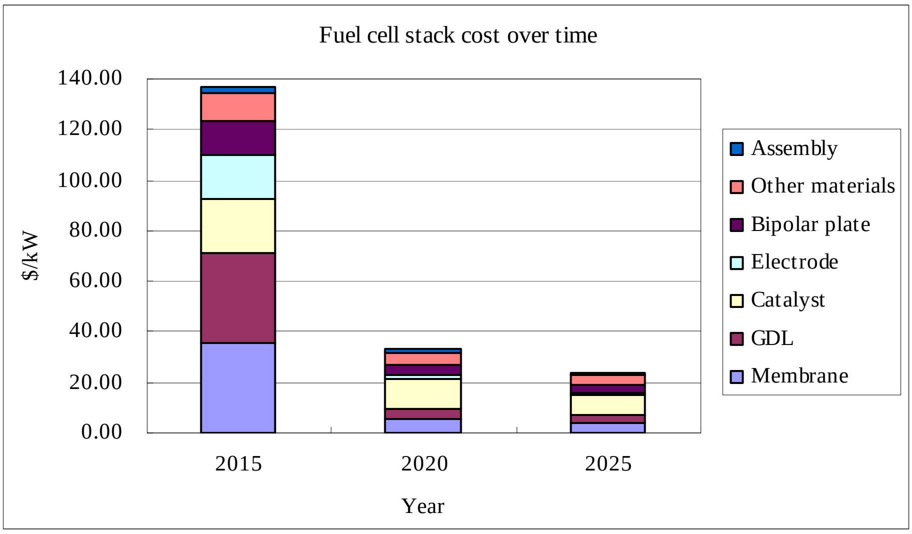


Figure 4-16 Fuel cell stack cost breakdown over time

To show the BOP change over time, we present the cost breakdown for fuel cell system in Figure 4-17 in which air, water, thermal and fuel represent four BOP auxiliary subsystems. Fuel cell stack cost declines over time and the fraction of fuel cell stack cost among fuel cell system also decreases over time due to technological advances and learning effects. The cost contribution of fuel cell stack in fuel cell system decreases from 84% in 2012 to 40% beyond 2020 though platinum price increases over time. By comparison, technology change yields relatively lesser cost savings and comes with reduced or eliminated components. Note that water management subsystem will be removed from the system beyond 2020.

In AVCEM, we calculate the retail cost to consumer for a hydrogen fuel cell vehicle to be about $27,715, around $5,000 to $6,000 more than a conventional gasoline vehicle, based on a 2025 platinum price of $2,503/troy-oz. If the platinum price were increased 50% above this level to $3,755/troy-oz, the fuel cell system cost would increase by about $4kW (6.6%), and the vehicle retail cost would increase by about $415 (1.5%). Note that increasing platinum prices would also increase the price of gasoline vehicles, which use platinum in catalytic converters.

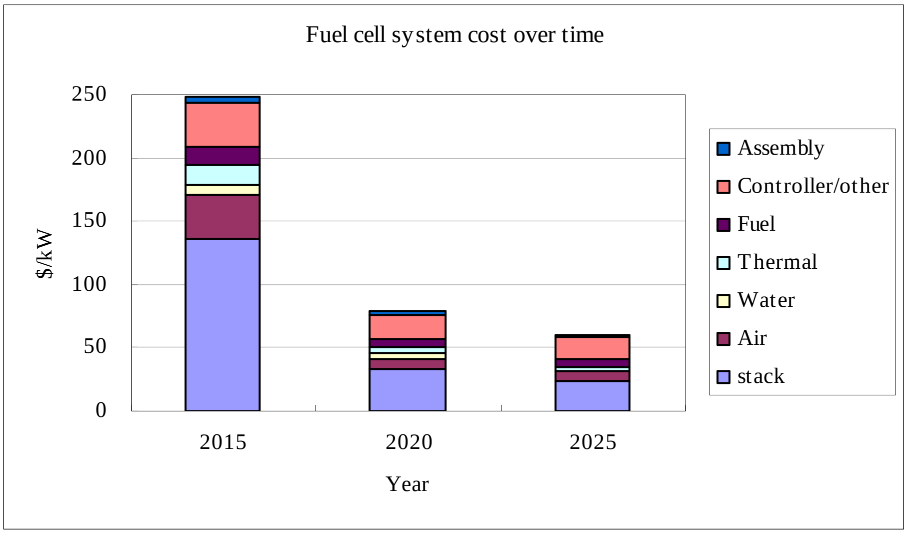


Figure 4-17 Fuel cell system cost breakdown over time

4.2 Hydrogen on-board storage system cost

We assume that hydrogen on-board FCVs will be stored at high pressure (up to 10,000 psi) in fiber-wrapped pressure vessels. AVCEM estimates the hydrogen storage tank cost in dollars per cubic feet of inner capacity of storage tank per 1000 psi of storage pressure, as a function of the storage pressure (psi) and production scale. The coefficients in the AVCEM functions have been adjusted to make the results approximately consistent with the literature estimates reviewed below. A reduced form of the calculations in AVCEM estimates the tank cost with mass production at a given storage pressure (10,000 psi) as a function of the weight of hydrogen (equation 4-8):

$$\text{H2 tank cost (2005 constant US \$)} = 467.76 * \text{full tank H2 fuel (kg)} + 50 \qquad (4\text{-}8)$$

Assuming a range of 300 miles over the Federal Urban Drive Schedule, the calculated full-tank hydrogen weight is about 4kg in 2025 for Scenario 3. Putting this into equation (4-8) results in a tank cost of about $1,900 or about $12/kWh-hydrogen, which is comparable to some other estimates in the literature. For example, TIAX (2004) and Argonne National Laboratories (ANL) estimated that for a mid-size vehicle with a 370-mile range in combined urban/highway driving, requiring 5.6 kg of hydrogen, a 5,000-psi tank cost $1,948, or $8.8/kWh, and a 10,000-psi tank cost $2,458, or $11.1/kWh. Carbon fiber was the major cost component. Similarly, Quantum (2006) indicates that hydrogen storage tank cost is in the range of $10-$17/kWh and carbon fiber contributes about 65% of system cost. More recently, TIAX, Argonne and other national labs (Lasher, 2007) conducted an independent cost assessment of hydrogen storage technologies based on the “Bill of Materials” plus an assumed processing cost, and estimated that a 10,000-psi tank system holding 5.6 kg of hydrogen costs about $3,450 or about $15.6/kWh.

According to the above studies, given the current technology, an on-board hydrogen storage system costs $9-$17/kWh. This hydrogen storage cost value is within the range ($8-$16/kWh) estimated by an expert panel convened by the California Air

Resources Board (Kalhammer et al., 2007), but significantly higher than the US DOE's goals of $2-4/kWh for hydrogen storage.

It is important to note that these cost estimates are based on a large production scale, typically an annual production volume of 500,000. Costs increase rapidly at lower production volumes. For example, the estimated storage system cost in AVCEM under scenario 3 decreases from $59.5/kWh at 1,000 units per year to $12.2/kWh at 2.5 million units per year.

4.3 Hydrogen fuel cell vehicle modeling results from AVCEM

With the estimated fuel cell system cost, hydrogen on-board storage system cost, and other vehicle related costs (motor, transmission, chassis, body, assembly, division cost, dealer cost, shipping and etc.) estimated in AVCEM, we calculate the retail cost to consumer for a hydrogen fuel cell vehicle to be about $27,600, around $5,000-$6,000 more than a conventional gasoline vehicle (Delucchi, 2005). Table 4-5 presents the cost summary of our hydrogen FCV modeled in AVCEM for year 2025 under DOE Scenario 3, when each fuel-cell system component achieves its long-run cost, i.e. each cost factor in equation 3-5 declines to 1. For DOE Scenarios 1 and 2, hydrogen FCV retail cost to consumer is over $100,000 initially, and decreases sharply in the first 5-7 years (Figure 4-18) as production volume increases over time, mainly because of fuel cell system cost reduction.

Table 4-5 Cost summary of our hydrogen FCV car as compared to our baseline gasoline vehicle (Table 4-2)

Component – manufacturing cost	2005 US $	Incremental costs compared to our baseline gasoline vehicle
Electric Powertrain (Motor + controller + transmission)	$348	-$1,612 No engine
Fuel cell system (stack + BOP)	$4,027	$4,027 Extra component for FCV
Hydrogen storage system	$1,978	$1,978 Extra component for FCV
Body	$2,008	$55 Greater reduction in weight than ICEV
Chassis	$2,425	$-673 No exhaust emission control system
Assembly	$1,733	-$8 About the same as ICEV
Total manufacturing cost	***$12,519***	***$3,767 Sum of the above incremental costs***
Division cost	$6,057	$693 0.3% increase per 1% increase in manufacturing cost
Corporate cost	$3,841	$376 0.15% increase per 1% increase in manufacturing plus division costs
Dealer cost	$3,946	$500 0.5% increase per 1% increase in factory cost
Manufacturers' suggested retail price	$26,362	$5,336 Incremental manufacturing plus division, corporate and dealer costs
Shipping cost	$402	$-122 Proportional to vehicle curb weight ($0.16/lb)
Sales tax	$803	$156 Incremental sales tax
Retail cost to consumer	***$27,567***	***$5,369 Total incremental retail cost to consumer***

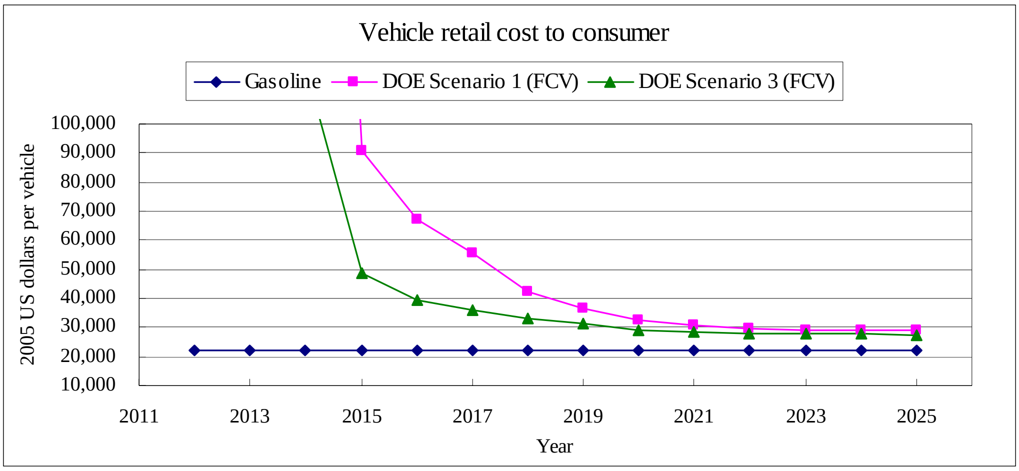


Figure 4-18 Vehicle retail cost to consumer over time

4.4 Hydrogen Fuel Cost Per-Mile

One of the major concerns for vehicle purchase is fuel cost, which depends on two aspects: fuel economy (energy use per miles) and fuel cost per unit of energy. The former is determined by vehicle performance and the latter by fuel production and delivery costs.

AVCEM contains a detailed energy use simulation model to calculate the amount of energy required for a vehicle with particular characteristics to move over a specified drive-cycle. All forces acting on the vehicle are simulated on a second-by-second scale over a specified drive cycle. The Federal Urban Drive Schedule (FUDS) is a relatively low speed drive cycle with average speed of 19.5 mph. In AVCEM, an adjusted FUDS shown in Figure 4-19 is created by multiplying the FUDS velocity points by 1.25. According to the simulation result under the adjusted FUDS, the fuel economy of FCVs would achieve 57 miles per gasoline-equivalent gallon (mpgge) for the current technology, several-fold better than the 20.1 mpg of the baseline conventional gasoline vehicle[4]. Although FCVs have higher fuel economy than gasoline vehicles, in the calculation of the fuel cost per mile this is somewhat offset by the higher cost per unit energy. The fuel cost is relatively high in part because hydrogen refueling stations have not yet been put into large-scale commercial operation, and fuel cost is higher in the early stages of infrastructure development.

[4] The AVCEM estimate is very close to the EPA-reported combined fuel economy of the 2006 Ford Taurus (20mpg) (http://www.fueleconomy.gov/feg/calculatorCompareSideBySidePopUp.jsp?column=1&id=22056).

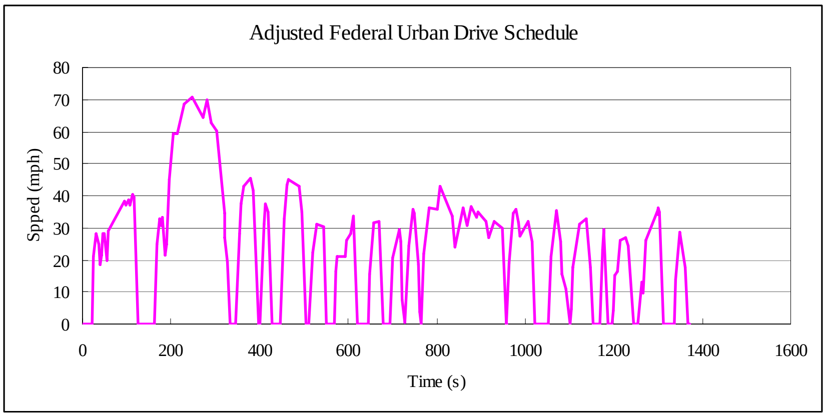


Figure 4-19 Adjusted FUDS in AVCEM

We use the NRC results (NRC 2008) for delivered hydrogen fuel costs. Using SSCHISM, the NRC study made several assumptions for a phased introduction of hydrogen infrastructure matching the hydrogen demand in each city, and costs and performance are based on H2A's technology assumptions for year 2015 from the H2A model developed by the U.S. DOE. Initially, five percent of existing gasoline stations is the minimum number of hydrogen stations to ensure adequate coverage and consumer convenience. At this point, station capacity is only 100kg/day with hydrogen from the existing industrial hydrogen system. Then, as demand begins to grow, 500 kg/day onsite steam methane reformers (SMRs) are built. As demand grows further, each station expands to be 1,500 kg/day. Later on, new hydrogen stations are added to meet more demand. The station capacity factor is assumed to be 70%. The estimated hydrogen fuel costs for scenarios 1 and 3 are shown in Figure 4-20, compared with the pretax gasoline price from the reference case of the EIA's AEO 2008 (our reference case).

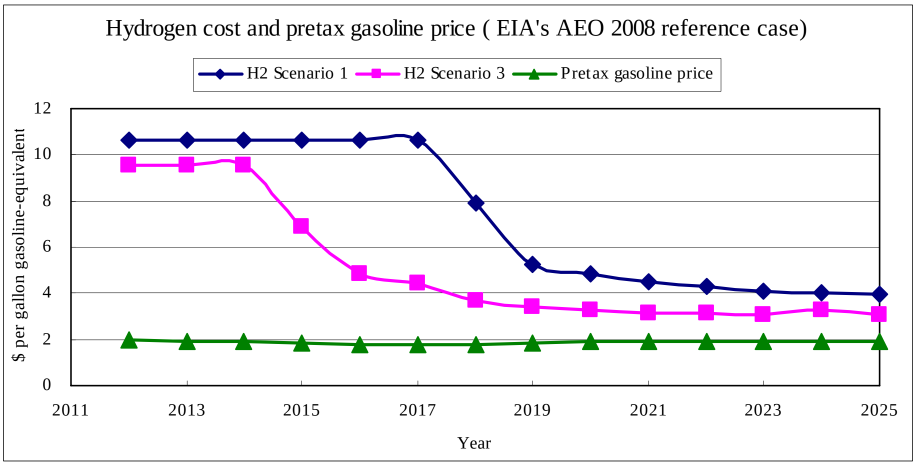


Figure 4-20 Delivered hydrogen fuel cost as estimated by NRC with SSCHISM

4.5 Periodic ownership and operating costs

The operating and maintenance cost (O&M), discussed in detail by Delucchi (2006), includes insurance, maintenance and repair, registration, fuel excise taxes, tires replacement, accessories and other fees, some of which are related to vehicle value, weight, and VMT (vehicle miles traveled). We use these results from AVCEM without any adjustments.

Chapter 5 Valuation of Externalities

As discussed in Chapter 4, vehicle first cost, fuel cost, and periodic ownership and operating cost are explicit private expenditures for consumer, but the use of motor vehicles costs society more than the private payments. Some social costs are priced or bundled in the prices of goods and services (Delucchi, 2004), such as road construction, highway petrol and military expense for defending oil supply in the public sector, and free parking at most shopping centers in the private sector. In addition to these monetary costs, vehicle use also involves nonmonetary costs that are not priced in the current markets. Examples include the health effects from air pollution and greenhouse gas (GHG) emissions, land-use damage, noise from vehicle operation, pain due to accidents, and sufferings from travel time. The total societal cost of motor vehicle use is the sum of all these costs mentioned above. This research aims to compare alternative fuel vehicles with conventional gasoline vehicles from the societal perspective. Some non-private costs, such as highway service establishments, travel delay and accident expenses, hardly make any difference across all vehicle types. However, most alternative options have significant advantages in terms of reductions in full fuel-cycle emissions of air pollution and GHGs, and external cost associated with oil use. Here we consider four types of externalities: air pollution, oil use, noise and GHGs.

We use the AVCEM model and additional analysis to estimate the external costs associated with oil use, air pollution, climate change, and noise. Oil-use costs comprise the cost of the Strategic Petroleum Reserve (SPR), macroeconomic costs from oil price shocks, wealth transfers from U.S. consumers to foreign oil producers (a cost only in the U.S. national accounting), the military costs of oil use, and the cost of water pollution due to oil use. Air pollution costs comprise health effects (such as premature mortality), reduced visibility, crop losses, and damages to forests and materials. The external costs of air pollution include the impacts of emissions from the "upstream" lifecycle of fuels as well as emissions from vehicle themselves, and the external costs of climate change include the impacts of emissions from the vehicle lifecycle as well as from the full lifecycle of fuels. The upstream lifecycle of fuels includes energy feedstock production, transportation and storage, and fuel production, transportation, storage and distribution. The vehicle cycle includes vehicle assembly and the lifecycle of materials used in vehicles.

5.1 External costs of oil use

The external costs of oil use per mile are calculated simply as the external cost per gallon of petroleum divided by the fuel economy. The fuel economy is calculated within AVCEM. The external cost per gallon is based upon a base-year (BY) value and an assumed rate of change, as shown in Table 5-1, where "*BY*" refers to base year that is the dollar-year (oil-use cost expressed as $/gallon in that year dollar value) estimated in the original study, and "*ROC*" is the assumed annual rate of change in the base-year value. The last column “Basis of ROC estimate” explains the reason for this assumption. Most of the estimates of the external cost per gallon are based on extensive analyses done by researchers at UCD and elsewhere (Delucchi, 2000, 2004a, 2004f, 2008a, 2008b, Stern, 2009, Leiby, 2007).

Table 5-1 External costs of oil use ($/gallon except as indicated)

Notes: BY = base year, ROC = annual rate of change in base-year value

Oil-use cost	***Low***	***Best***	***High***	***BY***	***ROC***	***Source of base-year estimate***	***Basis of ROC estimate***
SPR	0.0004	0.0010	0.0052	1991	2.5%	Delucchi (2004f)	Assume increases with GDP
Defense of oil	0.068	0.216	0.685	2004	0.0%	Delucchi & Murphy (2008a, 2008b) estimate $0.03 to $0.15 per gallon of motor fuel, including about 6% non-petroleum components on average; thus, dividing by 0.94 yields the cost per gallon of oil. Based on a recent study by Stern (2009), we update the estimates to be $0.069-$0.685 per gallon of oil.	Delucchi & Murphy's (2008a, 2008b) analysis suggests that total cost increases at the rate of increase in fuel consumption, which suggests a stable $/gallon cost.
Pecuniary externality	0.033	0.088	0.155	2000	1.5%	Leiby (2007) estimates "monopsony" or demand-related wealth-transfer costs of $2.77 to $13.11 (best: $7.41) per bbl of imported oil, and reports that imported oil is 58.6% of total oil demand; thus, we assume that 58.6% of motor fuel comes from imports. However, it appears that Leiby's (2007) estimate includes what we estimate as producer surplus; to account for this, we reduce Leiby's (2007) estimates by 15%.	Assume increases with price of oil.
Price-shock GNP cost	0.029	0.064	0.103	2005	1.5%	Leiby (2007) estimates "macroeconomic disruption /adjustment costs" of $2.10 to $7.40 (best: $4.59) per bbl of imported oil, and reports that imported oil is 58.6% of total oil demand; thus, we assume that 58.6% of motor fuel comes from imports.	Base year from Leiby (2007). Factor increase assumed to be rate of increase in oil prices.
Water pollution	0.0023	0.004	0.0076	1991	2.5%	Delucchi (2000, 2004a).	Assume increases with GDP.

Note that in this analysis we calculate social costs both from a US perspective and from a global perspective. The pecuniary externality (Table 5-1), which results from oil price changes, is a real cost to the US from the perspective of the US, but from a global perspective it is an international wealth transfer and not a social cost (to be deducted).

5.2 External costs of air pollution

As mentioned above, we make separate estimates of air pollution damage costs due to emissions from motor-vehicles and air-pollution damage costs due to emissions from the upstream lifecycle of fuels. In general, the air pollution damage cost per miles is the product of a per-mile emission rate (e.g., g/mile) and a per-gram damage cost (e.g., \$/g). Our estimates of g/mile motor-vehicle emissions are for model-year 2015 light-duty gasoline vehicles from the LEM (Delucchi, 2003). We use half of the estimated values for our calculations in AVCEM as shown in Table 5-2, assuming that vehicles reach the midpoint of their lives in about year 2020.

Table 5-2 Motor-vehicle emissions in g/mile used in AVCEM

Air pollutant	Emission rate
NMOC tailpipe	0.125
NMOC evaporative	0.110
NOx	0.235
CO	1.750
SOx	0.017
PM	0.010

Our estimates of the per-gram damage costs of motor-vehicle emissions, shown in Table 5-3, are based on detailed models of the relationships between emissions, air quality, physical impacts, and economic welfare (McCubbin and Delucchi, 1996 report #11, Delucchi et al., 1996 report #12, #13), updated from their original 1990 baseline as described in Delucchi (2006) (Delucchi, 2006).

Table 5-3 Vehicle-related air pollution damage cost from AVCEM (in 2005 dollars per tonne)

	Low	High	Medium
NMOC tailpipe	1410	46248	8075
NMOC evaporative	1410	46248	8075
NOx	3624	72798	16242
CO	14	141	45
SOx	17766	240856	65414
PM	19881	269874	73249
Benzene	160	1599	506
Formaldehyde	0	0	0
1,3-butadiene	1808	29827	7343
acetaldehyde	0	1185	0

Note: Medium value is the geometric average of low-cost and high-cost.

Our estimates of upstream fuel-cycle emissions (g/mile) are from the LEM, for the year 2020. Table 5-4 shows the LEM estimates and estimates from GREET version 1.7 (Wang et al., 2007) for comparison. Most LEM values are higher than those from GREET, on account of differences in assumptions and methods in the two models. GREET projects higher upstream PM emissions than the LEM because the LEM takes into account emission reductions due to emission controls while GREET does not.

Table 5-4 Upstream air pollution in grams per mile from LEM and GREET 1.7

	LEM (2020)		GREET 1.7 (2020)	
Air pollutants	Gasoline	FCV	Gasoline	FCV
NMOCs	0.149	0.015	0.124	0.021
NOx	0.301	0.197	0.208	0.113
CO	0.262	0.134	0.070	0.051
SOx	0.206	0.065	0.103	0.091
PM	0.009	0.005	0.056	0.065

Note: NMOCs=nonmethane organic compounds, NO_x=nitrogen oxides, and PM=particulate matter

To estimate $/g damages of emissions from the upstream lifecycle of fuels, we adjust our estimates of motor-vehicle $/g damage costs for differences in exposure to motor-vehicle air pollution versus upstream air pollution. This adjustment is done on the basis of the analysis of Delucchi and McCubbin (2006), who develop a Gaussian dispersion air quality model to estimate a set of normalized terms. These terms are the fraction of emissions from each upstream source reaching the ambient air quality monitors, relative to the fraction of direct emissions of fine PM from light-duty gasoline vehicles reaching the ambient air quality monitors. The normalized dispersion terms, or ratios, are the contribution to ambient pollution per unit of emission for each pollutant and emission-source category, relative to the contribution of light-duty gasoline motor-vehicles. To account for considerable uncertainties and site variabilities, low and high values are assumed for the estimated ratios. According to this definition, a higher value of the normalized term for non-motor-vehicle sources results in a lower dollar cost of motor-vehicle air pollution and vice versa. Here we apply the ratios estimated for urban monitors within an US average county for our analysis and assume that, in general, three of the emission categories are matched with the three upstream fuel-cycle stages, as shown in Table 5-5. An important exception is hydrogen production. Because we assume hydrogen from onsite SMR, we match hydrogen production with the fuel-storage, distribution, and dispensing stage instead of the fuel-production stage. As the estimated ratios are almost the same across their studies pollutants, we use only one set of values for the five pollutants presented in Table 5-4.

Table 5-5 Relative contribution of upstream air pollution to ambient air quality

Stage of upstream	Emission-source category	low	high
Feedstock activities	Agricultural and forestry, and managed burning; natural gas extraction	0.42	0.12
Fuel production	Chemistry and allied product manufacturing; metals processing; petroleum refining; other industry	0.38	0.06
Fuel storage, distribution, and dispensing	Solvent utilization, storage and transport; waste disposal; recycling, onsite hydrogen production	0.59	0.20

Note: Low and high refer to motor-vehicle-related damage costs from air pollution.

Table 5-6 Upstream air pollution damage cost (in 2005 constant dollars per metric ton)

Stage	Air pollutant	Low	High	Medium
Feedstock activities	NMOCs	592	5550	1813
	NOx	1522	8736	3646
	CO	6	17	10
	SOx	7462	28903	14686
	PM	8350	32385	16444
Fuel production	NMOCs	536	2775	1219
	NOx	1377	4368	2452
	CO	5	8	7
	Sox	6751	14451	9877
	PM	7555	16192	11060
Fuel storage, distribution, and dispensing	NMOCs	832	9250	2774
	NOx	2138	14560	5579
	CO	8	28	15
	SOx	10482	48171	22471
	PM	11730	53975	25162

The upstream air pollution damage costs for the three stages (feedstock activities, fuel production, and fuel storage, distribution and dispensing) shown in Table 5-6 are estimated by multiplying the vehicle-related damage costs in Table 5-3 by the corresponding damage ratio in Table 5-5. For instance, under a low case, the damage cost of the CO emission from feedstock activities in dollars per metric ton is 14 times 0.42.

Table 5-7 presents the upstream air pollution for each stage, as a percentage of the total upstream emissions, for the two vehicle options. For each pollutant, we multiply these percentages by the total upstream emissions in Table 5-4 to obtain the emissions from each stage, which are then multiplied by per-unit damage costs from Table 5-6 to obtain the total upstream damage cost in dollars per mile.

Table 5-7 Fractions of air pollution from each stage of upstream activities from LEM

		NMOCs	NOx	CO	Sox	PM
Gasoline	Feedstock activities	0.21	0.60	0.71	0.73	0.55
	Fuel production	0.07	0.34	0.24	0.21	0.43
	Fuel storage, distribution, and dispensing	0.72	0.06	0.05	0.06	0.02
FCV	Feedstock activities	0.79	0.51	0.74	0.19	0.72
	Fuel production	0.11	0.27	0.15	0.22	0.11
	Fuel storage, distribution, and dispensing	0.10	0.22	0.11	0.59	0.17

5.3 External costs of climate change

The cost per mile of damages due to climate change is calculated as the product of g/mile GHG emissions from the fuel and vehicle lifecycle and $/g damages from emissions of GHGs. Estimates of lifecycle CO_2-equivalent GHG emissions are from the LEM. The *global* climate-change damage cost in dollars per metric tonne carbon ($/tC) is assumed to be $5/tC in the low case, $16/tC in the medium case, and $150/tC in the high case, based on Tol's result (2005) from an assessment of 28 published studies on marginal cost of CO_2 emissions and recent work by Repetto and Easton (2009). The climate-change damage cost to the U.S. alone, which is relevant when takes a U.S.-only as opposed to a global perspective, is much lower, partly because the U.S. is wealthier than the rest of the world and partly because the US might suffer less severe effects than will some other countries. On the basis of a review and analysis of the literature (Delucchi, 2004a, Repetto and Easton, 2009, Pearce, 2003, Tol, 2003), the GHG damage cost in the US is assumed to be $0/tC in the low case, $1.2/tC in the medium case, and $17.4/tC in the high case.

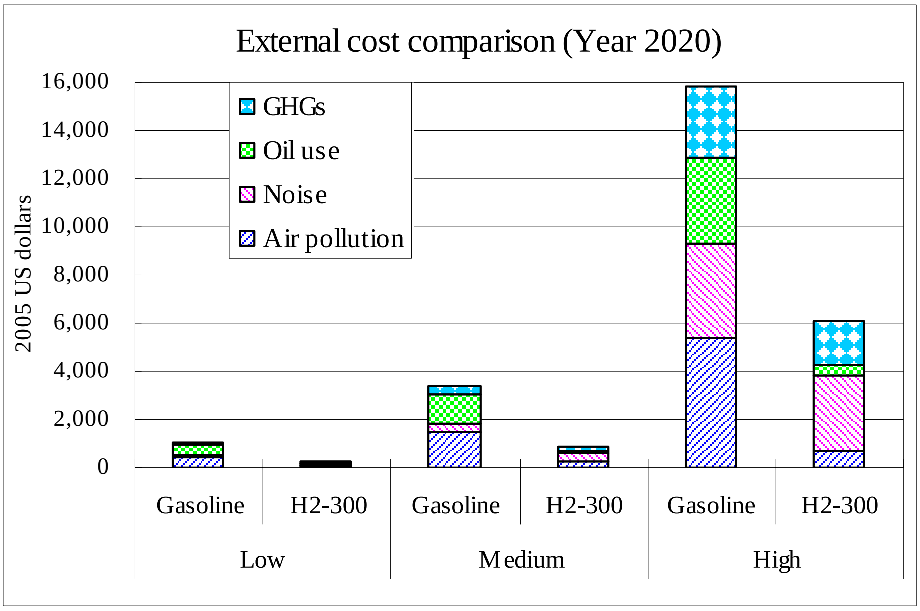
5.4 External costs of vehicle noise

Estimates of the damage cost per mile of noise from gasoline vehicles are from Delucchi and Hsu (1998). AVCEM assumes that hydrogen FCVs produce slightly less noise, and hence have slightly lower noise-damage costs, than do gasoline ICEVs, because electric powertrains generally are quieter than engines. Noise damage costs from gasoline vehicles in cents per mile in 1991 US dollars are assumed to be 0.02 in the low case, 0.20 in the medium case and 2.00 in the high case. For hydrogen FCVs, we assume the noise damage costs (cents/mile) are 0.14 in the low case, 0.15 in the medium case and 1.6 in the high case. Upstream emissions are from LEM

5.5 Comparison of total external costs

Figure 5-1 shows our low, medium and high estimates of the present value of the external costs of gasoline ICEVs and hydrogen FCVs over the same annual vehicle miles traveled (VMT) (about 10,000 miles) and same vehicle lifetime as ICEVs

(150,000 miles). Hydrogen FCVs have longer lifetime than ICEVs, which will be discussed in Chapter 7. The discount rate for externalities is set at 3% for present value calculations. Hydrogen FCVs have significantly lower external costs of air pollution, climate change, and oil use. Enlarged figures for the low and medium cases are shown below. The present value of this difference is less than $1,000 in the low-external-cost case, but is over $2,000 in the medium-external-cost case and over $7,000 in the high-external-cost case. Air-pollution damage cost is the biggest external cost for gasoline vehicles. Noise-damage cost is a major cost in the high-external-cost case because we assume the cents/mile damage cost of noise in the high case is ten times that in the medium case.



Note: H2-300 refers to hydrogen FCV with a range of 300 miles

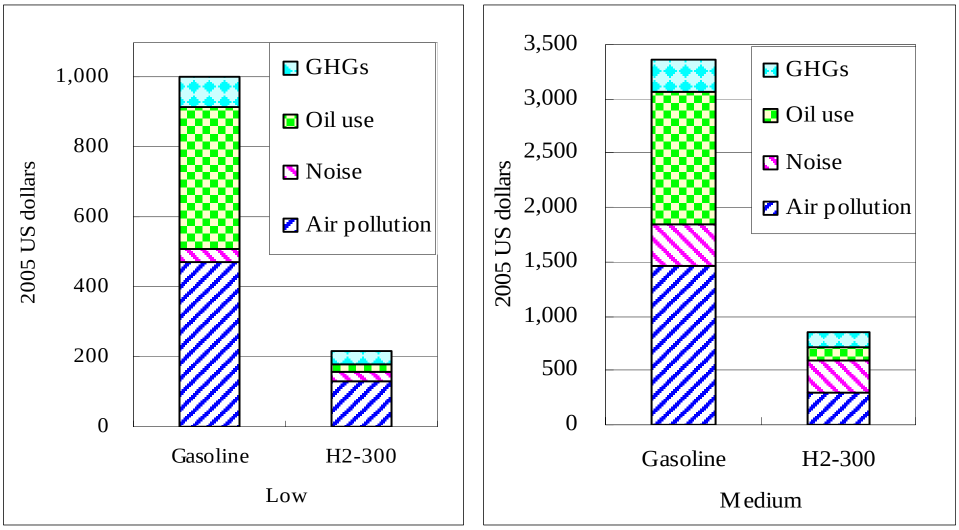


Figure 5-1 External cost comparison in present values (global accounting)

To compare hydrogen FCVs with other vehicle options in terms of external cost, Figure 5-2 presents the cents/mile results in the medium case in 2020 for conventional gasoline vehicles, battery-powered electric vehicles with a range of 150 miles (BPEV-150), hybrid electric vehicles (not plug-in hybrids) with a range of 35 miles on battery only (HEV-35) and hydrogen FCVs. For BPEV150 and HEV-35, upstream fuel-cycle emissions are still from the LEM, shown in Table 5-8, and we use the default values in AVCEM for other vehicle-related costs and performance (NiMH battery). We assume U.S. grid mix for electricity generation for charging battery used in BPEV and HEV. Vehicle cost and fuel economy in 2020 calculated in AVCEM are included in Table 5-9. Note that the results for BPEV and HEV in Table 5-9 are at current level, estimated in AVCEM. With battery technology progress over time, vehicle cost will decrease and fuel economy will improve, but probably the extent will be much less than hydrogen FCV. We do not consider this in the comparison.

Table 5-8 Upstream air pollution in grams per mile from LEM

	LEM (2020)	
Air pollutants	BPEV	HEV[5]
NMOCs	0.022	0.097
NOx	0.788	0.480
CO	0.193	0.229
SOx	0.904	0.469
PM	0.228	0.093

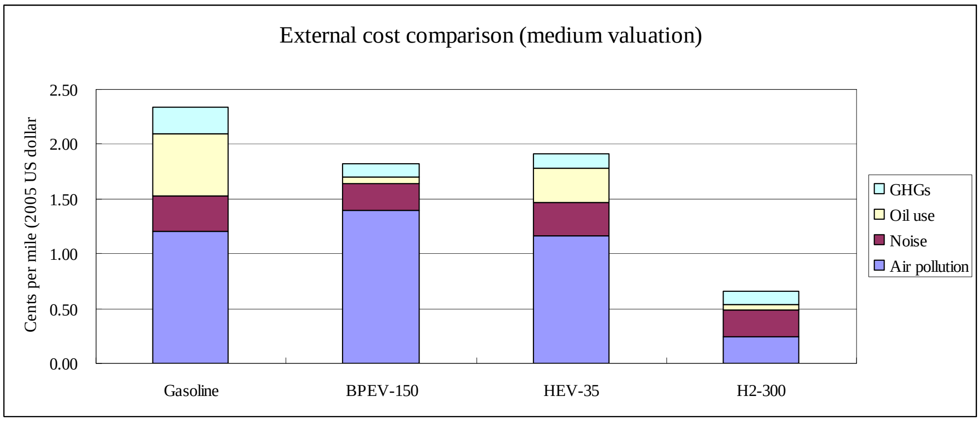


Figure 5-2 External cost comparison in cents per mile (Global accounting)

Table 5-9 Summary of vehicle cost and fuel economy in 2020 calculated in AVCEM

	Gasoline	BPEV-150	HEV-35	H2-300
Vehicle retail cost	$22,198	$26,807	$24,955	$29,304
Fuel economy (mpg)	28.8	117.8	37.1	66.9

Note: Fuel economy values for BPEV, HEV and FCV are gasoline equivalent mpg (miles per gallon).

Among the four vehicle types shown in Figure 5-2, a hydrogen fuel cell vehicle has the lowest total external cost. In particular, a hydrogen FCV has much lower air pollution damage cost, compared with a BPEV or HEV. Total external cost for a hydrogen fuel cell vehicle is about 0.66 cents/mile, less than one-thirds of that for a BPEV. The damage cost of air pollution from a hydrogen FCV is about one-sixth of that from a BPEV, and about one-fifth of that from a HEV.

[5] The emission rate for HEV is calculated based on energy distribution from internal-combustion engine and battery, with emission rates in grams per MMBtu for gasoline vehicles and BPEVs.

Chapter 6 Non-cost Social Transfers

Among consumer/private lifetime cost of vehicles, expenses such as taxes and fees, producer surplus on payments for fuel, and producer surplus on payments for vehicles are costs to consumers but are wealth transfers from the perspective of society. Hence, these three items should not be treated as social costs per se. In this chapter, we present detailed analysis for producer surplus associated with gasoline fuel.

6.1 Taxes and Fees

Using information from FHWA (Federal Highway Administration), AVCEM calculates the current fuel taxes on gasoline on a cost-per-miles basis (cents/gal divided by miles/gal) that includes federal, state, and local excise taxes. A scaling factor, which is specified by the user, represents the cost-per-mile excise taxes ratio of other vehicles to gasoline vehicle. The ratio is set as one in the base case, i.e. all vehicles pay the same fuel taxes per mile. Although initially fuel tax policy might be used to give an advantage to alternative fuels, ultimately the revenues from the fuel tax would have to be replaced if alternative fuels became important. Fuel taxes are counted in the O&M cost category as a cost item of consumer cost, and deducted in the social-cost accounting.

6.2 Producer Surplus associated with Gasoline Fuel

Alternative fuels are appealing to the transportation sector because they provide both energy security and environmental advantages over conventional petroleum fuels. Another benefit of alternative fuels is that they have low social costs. These benefits are factored into the social cost-benefit analysis used to evaluate alternatives to petroleum. Under the assumptions that all alternatives offer the same non-cost vehicle amenities (performance, cargo capacity, etc.), alternatives can be compared strictly on the basis of social cost, which is the area under the long-run marginal cost curve, and is different from price-times-quantity revenues or payments. When societal cost is employed to evaluate various transportation fuels in the US, one should calculate actual domestic resource costs incurred to explore, develop and produce fuels, and the expenditures on imported oil. In the Advance Vehicle Cost and Energy Use Model (AVCEM) (Delucchi, 2005), consumer cost involves vehicle cost, fuel cost and operating & maintenance cost, where the fuel cost to the consumer, which is the price times quantity consumed, includes the producer surplus that should be deducted for the societal cost estimate.

Producer surplus (PS) is any revenue *above* the total long-run cost including a normal rate of return. When estimating the PS associated with various fuels, AVCEM makes a distinction between a U.S. national accounting and a global accounting. With a U.S. national accounting, for example, wealth transfers outside of the U.S. are a cost to the U.S. With a global accounting, all wealth transfers between countries are transfers and not social costs. Thus, the PS received by foreign oil producers is a real cost to the U.S. from the US' perspective, not from a global perspective. Therefore, we deduct PS from fuel cost – that is, we do *not* count it as a social cost – only in the global perspective accounting.

We are interested in estimating PS for transportation fuels as it is pertinent to social cost-benefit analysis for comparing alternatives with petroleum-based fuels. We discuss two different kinds of PS for two different purposes when consumption changes. One is total producer surplus change (we call this $\triangle PS_t$ where t stands for "transfer") for estimating wealth transfer from consumer to producer. The other is producer surplus fraction on changed consumption (we call this PSf_{ac} where ac stands for "average cost") for estimating average cost. We give an example to illustrate the difference between the two kinds of PS. Suppose the US consumes 35 billion gallons of gasoline (Q) annually and the gasoline price (P) is $2.5/gal (excluding taxes). Then the total payments PQ are $87.5 B, among which we assume 40% of PQ is PS ($35B). So the $\triangle PS_t$ is $35B and PSf_{ac} is 40% for a 100% reduction in gasoline use. These indicate that there is $35B transfer from consumer to producer and the average cost (AC) as a fraction of price for producer is 60% ($AC/P=1-PSf_{ac}$). We estimate $\triangle PS_t$ in terms of consumer welfare and estimate PSf_{ac} for producer's cost.

When both consumption and price change, $\triangle PS_t$ can be further broken into two components: one from consumption change and the other from price change.

Following the above example, we assume the US gasoline use reduces by 20% to 28 billion gallons and gasoline price drops to \$2.2/gal. Lower price spurs additional consumption (consumer gains) and actual consumption is assumed to be 30 billion gallons. PS change from consumption change is based on the actual use reduction (5 billion gallons) and PS change from price change is over the actual use (30 billion gallons), relevant to wealth transfer from the US to foreign producers. Over the initial consumption reduction (7 billion gallons), we can calculate the PSf_{ac}, which indicates the US producer's average cost.

We investigate the total cost for crude oil supply in the United States, focusing on the three main stages (exploration, development and production) in 2003 and 2004, and then derive the gasoline supply curve for the producer surplus calculation. Econometric models are used to develop the U.S. 2004 oil supply cost curve and then project future oil cost curves.

6.2.1 Discussion of Producer Surplus

In a social-cost analysis, we are interested in total long-run real (economic) cost incurred to produce a good, including both explicit accounting costs and implicit costs. The total economic cost can be calculated as the area under the long-run marginal cost (MC) curve. The total revenue a producer receives from selling a good in the market is the market price of the good times the quantity of the good sold, and consists of two parts. The first part is the producer surplus, which is the area above the producer's marginal cost or supply curve and below the price, and which measures the benefit that a producer receives for selling a good in the market. Figure 6-1 illustrates the producer surplus (shaded area) in an imperfect market for some firm with marginal cost (MC_0) below market price (P_0). (We use an imperfect market in our illustration here because this better characterizes the world oil market, but as we discuss below, producer surplus exists in perfectly competitive markets.) The second part of the total revenue is the cost to the producers of producing the good, or the area under the marginal cost or supply curve, and represents the resource cost of producing the good. However, in some cases, we do not have data on long-run MC, but only on price-times-quantity (PQ) revenues. In these cases, we have to estimate long-run MC – which is what we are interested in -- by subtracting producer surplus (PS) from PQ revenues.

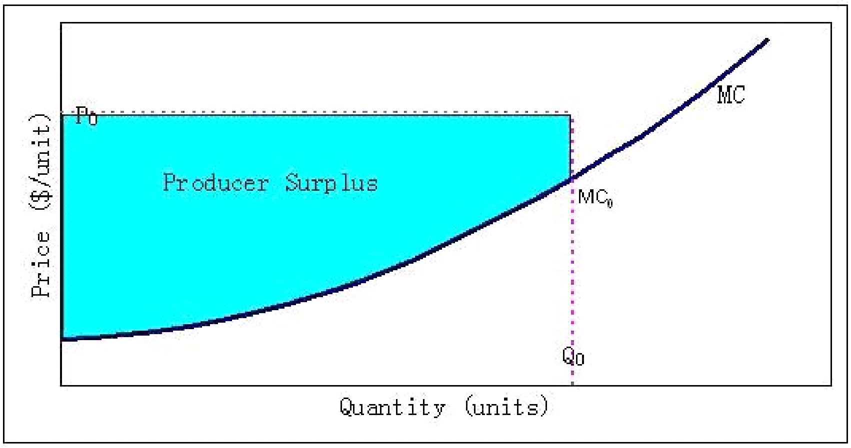


Figure 6-1 Producer Surplus in an imperfect market

The producer surplus of gasoline fuel is a wealth transfer from consumers to producers within the society, not a social cost. When alternative fuels are compared using a social-cost-benefit analysis, the comparison should be based on their long-run MCs, and PS should be viewed as a social transfer instead of a cost and therefore should not "count" as a social cost. An example will help make clear the importance of comparing alternatives on the basis of economic cost (and hence of subtracting PS from PQ revenues).

Table 6-1 presents a case with two fuel types I and II produced by two different firms A and B. Suppose markets for both fuels are perfectly competitive in long-run equilibrium with no market failures or any external costs, and they provide the user identical benefits. The only difference is in the production cost, which is $20/MBTU for Firm A and $40/MBTU for Firm B. The difference is that firm A is endowed with large reserves of fuel I that can be recovered easily with little effort; specifically, the labor requirement by firm A is only half of that by firm B for the same production level. It is clear that society prefers fuel I because it has lower social resource cost for the same level of benefits. However, for our cost-benefit analysis to reflect this, we need to estimate the long-run MC directly (from the "bottom up," based on the amount and cost of individual inputs) or subtract the PS from the PQ revenues.

Table 6-1 Two-fuel case

Firm	Fuel type	Selling price	Value to consumer	Marginal cost of production	Producer surplus
A	I	$50/BTU	$55/BTU	$20/BTU	$30/BTU
B	II	$50/BTU	$55/BTU	$40/BTU	$10/BTU

There are a number of terms and concepts that are inter-related and sometimes defined differently in different sources. These include producer surplus, economic profit, normal profit, accounting profit, economic rent, economic cost, accounting cost, and long-run marginal cost. We provide a glossary in Table 6-2 according to some microeconomics textbooks (Nicholson, 9th Edition, Pindyck and Rubinfeld, 6th Edition). Their relations are shown in Figure 6-2.

Table 6-2 Glossary of some costs and profits

Producer surplus: return received by producers from selling goods at the market price over and above their long-run marginal costs.
Economic profit: total revenue minus explicit and implicit costs. Economic profit is zero in long-run equilibrium in perfect competition.
Explicit cost: accounted cost that firms have to pay in the form of money, same as accounting cost.
Implicit costs: opportunity cost, or foregone money receipts, resulting from using resources instead of renting, selling or lending them.
Normal rate of return: the return that producers consider necessary to run the business. In a perfect market, competition makes economic profit be zero in the long run, but firms earn normal profit.
Normal profit: based on a normal rate of return, which basically equals “opportunity cost of resources supplied by owners of firm” (Frank and Bernanke, 2003) (implicit costs). Economic profit in the long run in perfect competition is zero, but normal profit is nonzero. Normal profit is a component of firm’s opportunity cost.
Accounting profit: total revenue minus explicit costs.
Economic rent: extra payment for an input that firms are willing to pay over the minimum amount necessary to remain it in its current use (opportunity cost of the input). Economic rent measures factor payment over and above opportunity cost while economic profit measures extra revenue over economic cost.
Economic cost: payment required to employ inputs for production, including both explicit accounting costs and implicit costs.
Long-run marginal cost: change in total cost for one more unit of output.

Under imperfect competition such as the oil market, the concentration of low-cost resources in a handful of countries and the agreement they behave like an oligopoly enable them to affect prices by controlling output. Oil suppliers produce less oil than that under perfect competition and the oil market price exceeds marginal cost. So producers can have a rate of return greater than the normal rate of return. If there were no such concentration or agreement, perfect competition in the industry would drive the market to a long-run equilibrium that price would equal marginal cost and equal average cost. Thus each firm would earn the normal rate of return and exactly zero economic profit. However, even in perfect competition owners of oil resources still would receive producer surplus as economic rent.

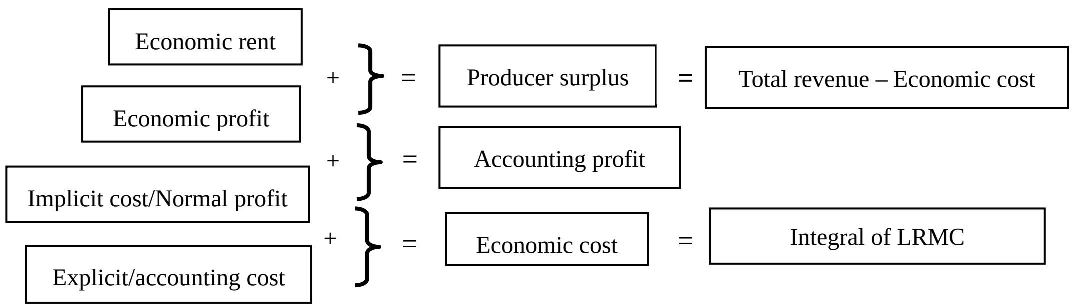


Figure 6-2 Connections between various economic concepts

Below is an example to illustrate these economic concepts. Suppose a farmer owns a parcel of extremely fertile land that is very rare. Total revenue to grow a crop on the land is $750, in an imperfect market, and the only input is the farmer’s labor. The farmer could earn $300 if she were to work outside this land; hence, the labor cost is $300. The producer surplus is $750-$300=$450. We assume the revenue would be $650 if market were perfect. Thus the economic rent associated with the land is $650-$300=$350. The economic profit is $750-$650=$100 (the difference between the actual revenue and the revenue that would be were the market perfect). In this case, there is no accounting cost. It is noteworthy that economic rent is related to a scarce resource (input factor) while producer surplus is related to gains on output, and producer surplus consists of economic rent and economic profit.

One important theoretical issue is that in a competitive market economic profit should be zero in the long-run equilibrium but producer surplus is not zero. In such case, the producer surplus consists of the economic rent that firms enjoy from all their scarce inputs. This is more important in oil markets because there are very large wealth transfers above and beyond real economic costs and there would be such transfers even if the market were perfectly competitive. To reconcile the zero economic profit with the apparent existence of producer surplus, we have to make a distinction between the long-run marginal cost curve and normal profit – the former determines producer surplus while the latter determines economic profit (see Figure 6-2). Producer surplus includes economic rent and economic profit. Economic cost (the integral of marginal cost) includes normal profit and accounting cost. Even if economic profit is zero, there still can be non-zero economic rent and hence non-zero producer surplus. The economic rent is the very reason. Some firms and regions are endowed with large oil reserves that can be recovered at very low cost. The abundant and cheap petroleum resources (oil rights) for those countries originally endowed with the low-cost oil are valuable and other entities are willing to pay for them, and the eventual price would be determined by the competition. The firms buying these oil rights would count it as a cost, which is sometimes called the “forgone-of-oil-rights cost". The payments are the economic rent enjoyed by the originally endowed regions but with zero economic profit. However, from the societal perspective, those payments associated with oil endowments are a wealth transfer, not a social cost. A key point here is that we should distinguish the foregone-of-oil-rights cost from resource costs such as drilling cost.

From a global viewpoint, producer surplus is a transfer from consumers to producers that is important in social cost analysis. However, when taking the US perspective, we also care about changes in PS transfer from the US to foreigner producers, due to changes in price because the PS changes are relevant to the cost to the US. Suppose the world oil price drops from $100/bbl to $50/bbl as a result of 75% oil consumption reduction in the US (such as alternatives to petroleum displace the 75% oil use). The PS reduction due to the price change indicates that the US payments to foreign oil producers decrease. In this situation, we count the PS as a cost to the US.

6.2.2 General Method of Analysis

In order to estimate the producer surplus associated with transportation fuels, we must first estimate the cost curves for petroleum fuels. With the estimated cost curves, we can find out the average cost as a fraction of price (complement of PSf_{ac}) presumably because we believe the fraction is less likely to change in the future as compared to an absolute term. The total change in PS ($\triangle PS_t$) is counted as a cost in some cases where we are interested in consumer welfare. Changes in the two kinds of PS with consumption reduction are relevant to energy policy implications in the US. This section begins by constructing the US oil supply curve based on the most recent data publicly available from American Petroleum Institute (API). We then derive the gasoline supply curve assuming that oil and gasoline costs have the same correlation as their prices, and use this to estimate the producer surplus for gasoline. Three energy-projection scenarios from the Energy Information Administration (EIA) Annual Energy outlook (AEO) 2009 are also examined to project future oil and gasoline supply curves for the producer surplus calculations.

In general, total oil costs involve exploration, development and production in which drilling and equipping exploratory and development wells are capital intensive, and production includes operating and maintenance. According to the API data (1989), the most recent year where disaggregated costs data are available, the estimated costs of drilling and equipping exploratory oil and gas wells were about 35% of total exploration cost, and the estimated costs of drilling and equipping development wells were about 60% of total development cost.

The costs of drilling wells are determined mainly by the well depth, diameter, casing design, and location specific characteristics. However, a large number of factors and events impact drilling performance and it is challenging to quantify well costs and complexity (Kaiser, 2007). The Joint Association Survey (JAS) is an authoritative source for drilling costs. The JAS employs a statistical model to estimate drilling cost using survey data. Tabulated data of average costs for drilling wells in the US from the Joint Association Survey (JAS) on Drilling Costs for the period 1976-2004 shows a general trend that drilling costs increase non-linearly with depth intervals (American Petroleum Institute, 2004, Augustine et al., 2006). We use the 2004 JAS data on oil wells for constructing the current oil cost function because the 2004 data is the most recent data available.[6] Oil cost is much higher in recent years relative to the 2004 level.

From the JAS and EIA data we can estimate the average production per well, and knowing the number of exploratory or development wells we can estimate the oil production in barrels. Based on historical data from American Petroleum Institute (API), we apply econometric modeling to derive functions for the relationships between oil exploration costs or oil development costs, and oil production levels. To construct the marginal cost curve for the oil production stage, we assume it has an exponential shape, and then calibrate those parameters with the data in years 2003 and 2004. Other exploration or development-related average costs are assumed to be independent of oil production levels. The sum of all these costs generates the oil marginal cost curve for 2004. For future oil marginal cost curves, we develop a regression model to find the trend in the average cost over time and shift the 2004

[6] According to the IEA World Energy Outlook 2009, the worldwide upstream oil and gas capital expenditures significantly increased between 2004 and 2008, from about $220 billion in 2004 to around $480 billion in 2008. The escalating expenditures on oil exploration and developments suggest that oil cost became much higher beyond 2004.

curve based on the projected average cost. Our analysis adopts the EIA AEO 2009 updated reference, high-economic-growth, low-economic-growth, high-price and low-price cases for the future oil supply, oil and gasoline prices, and reserves projected through 2030 in the US. These projections are based on results from the EIA's National Energy Modeling System (NEMS). To estimate the gasoline supply curve, we further assume that gasoline costs versus oil costs and gasoline prices versus oil prices have the same correlation. We also estimate the oil cost curves for OPEC and ROW with data from World Bank as compared with the US case.

6.2.3 Literature Review

In this section, we review studies that are relevant to our general method of analysis, including studies of oil production cost, factors that affect oil supply cost according to theory, oil supply projection, and the estimation of producer surplus generally.

Biedermann (1961) estimated a cost function for crude oil production based on empirical data, considering three major factors--drilling costs, well operating costs and cost of physical waste and depletion--that affect the cost of getting crude oil from the reservoir to the top of well. The US average drilling cost per well and average depth per well in 1953 were fitted with a quadratic function. Linear cost-output relationships within certain limits were assumed for well operating costs for both short-run and long-run considerations. Depletion and waste costs were modeled as a function of production rate, exploitation rate, expected oil price, reservoir (or oil field) lifetime and interest rate. A hypothetical relationship was assumed between exploitation rate and production rate, which was only valid for a given production mechanism under certain geological conditions of a reservoir. Given its outdated data for regression and function derivation from certain cases, it is not reliable to generalize this method.

Cleveland (1991) argued that two opposing forces--technical change and resource depletion--determine the long-run average cost of oil discovery and production. A U-shaped cost path hypothesis was empirically tested with the lower 48 U.S. data from 1936 to 1988 on the quantity and dollar cost of oil added to reserves and extracted. The interplay between short- and long-run effects was also explained: the short-run cost curve depicted how average cost changed with the rate of exploratory or development effort at a particular point on the long-run curve. The two dominant cost factors (stock effects and technological progress) were further examined by Lin and Wagner (2007) to extend the Hotelling model (1931) of optimal resource extraction. Data on 14 minerals for the period 1970-2004 were used to confirm that extraction costs increase with cumulative extraction (stock effects) and decrease with technological progress over time. Lin et al. (2009) modeled mathematically the endogenous technological progress as a cost shifter to predict when world oil reserves would be depleted if a constant market price was maintained. Extraction cost for energy resources as a nonlinear function of cumulative extraction was also applied by

Chakravorty (1997) for analyzing the effects of technological change in cost reductions on the backstop technology on resource extraction. These studies conclude that the long-run average cost of oil supply should be attributable to reserves and technology advance.

Adelman (1991) used two methods to measure the investment cost per incremental barrel of oil, one of which was based on supply curves. An exponential cost function (price P against reserve-addition Q) was assumed to characterize the US oil supply curves corresponding to a given price. The curvature was indicated by a slope coefficient (an empirical constant $c=\ln(P+1)/Q$), showing cost varying over time. Survey on studies of simple energy supply models by Dahl (1996) suggests that including reserve depletion and price expectations can improve the estimates for oil price elasticity when using a supply equation directly. These imply that reserves and price expectations are influencing factors for investment on oil production.

EIA develops the NEMS (2010) to project the world oil price and crude-like liquids supply with regional detail by simulating the interaction between U.S. and global petroleum markets. A uniform supply/demand function with constant elasticity is employed to model the supply-demand equilibrium with assumptions on economic growth and expectations of future U.S. and world crude-like liquids production and consumption. Within NEMS, the Oil and Gas Supply Module (OGSM) (EIA, 2010) projects U.S. crude oil and national gas production based on forecasted profitability to explore and develop wells for each region and fuel type. For crude oil, drilling and equipping costs per well are modeled as a polynomial function of well depth with 2004-2007 data from JAS. The NEMS model makes various assumptions to model each of the many components of cost separately, including cost of chemical handling plant, lifting costs, secondary workover, etc. It also models the number of patterns drilled each year, which requires additional assumptions. In contrast, our model is more parsimonious and requires fewer assumptions, as it finds relationships between marginal cost and production without making too many assumptions.

An accurate analysis of oil production and supply at a national or global level is difficult due to the lack of transparency within the oil industry, and due to the many political, technical and economic considerations that determine production rates. The first model to address the economics of exhaustible resources was discussed by Hotelling (1931) for scenarios of free competition, maximum social value, monopoly, and duopoly. Geophysicist M. King Hubbert (1956) used a symmetric, bell-shaped crude oil production curve to predict that the world oil peak would occur around 2000 and the US oil production peak around 1970, though such symmetric curves were questioned for describing the global case (Bardi, 2005). Global oil production may peak or plateau in near future due to many factors constraining investments into exploration and production instead of due to limited resources (Kjärstad and Johnsson, 2009). There is great uncertainty for the future oil supply/demand balance.

To estimate the producer surplus fraction of payments for gasoline fuel, Delucchi (2004) characterized the long-run marginal cost curve with a nonlinear function developed by Leiby (1993) for U.S. oil producers, OPEC, and the rest of the world. From Leiby's estimates for three parameters (lower oil price limit, upper bound on supplies, and curve shape) for U.S. oil producers, PS is about 40% of PQ receipts. For the downstream producers (refiners and marketers), Delucchi assumes that 20% to 30% of pre-tax retail cost of gasoline fuel and diesel fuel is PS. Leiby used the data from EIA 1993 AEO to construct oil supply curves, which may be not appropriate for the current analysis because of the outdated data.

These previous studies indicate that oil supply cost is determined by many factors, including well drilling, well operation, reserve depletion and technological change. Generally, oil cost increases nonlinearly with oil output, and technological change and reserves are two important factors that affect the average cost of oil supply in the long run. We attempt to model the US oil cost as an exponential function of oil output, considering exploration, development, production and other related costs. Recent data from the JAS and EIA are used to characterize each cost component in detail. Based on prior theoretical studies and EIA's projections, we also estimate the future oil cost in the US. More importantly, with our estimates of oil supply costs, we discuss two different kinds of producer surplus: $\triangle PS_t$ and PSf_{ac}.

6.2.4 Detailed Analysis

This section estimates the producer surplus associated with 10% and 100% reductions in gasoline fuel use in the US by deriving gasoline supply cost curve. We first estimate the current US oil supply curve and derive the US gasoline supply curve, and then discuss current world supply curve due to different data sources. Future US oil supply curves are estimated based on the current estimate and EIA projections.

6.2.4.1 Current US oil supply curve

The current US oil supply curve includes exploration, development, production and other related costs. We use the current detailed cost data to model the relationship between total oil marginal cost in dollar per barrel (including exploration, development, production, and other related costs) and oil output in barrels. Formally, the overall equation is as follows:

$$MC_{oil} = MEC + MDC + OED + MPC \qquad (6\text{-}1)$$

$$MEC = f_E(Q), \quad MDC = f_D(Q), \quad OED = C_{OED}, \text{ and } \quad MPC = f_P(Q)$$

Where:

MC_{oil} = marginal cost of oil (2005 \$/bbl)

MEC = marginal exploration cost of oil (2005 \$/bbl) including costs of drilling and equipping wells for exploratory wells

MDC = marginal development cost of oil (2005 \$/bbl) including costs of drilling and equipping wells for development wells

OED = other exploration and development –related marginal cost (2005 \$/bbl)

MPC = marginal production cost of oil (2005 $/bbl) including operation, administration and other expenses

f_E, f_D, C_{OED}, and f_P are marginal cost function formulae to be estimated by fitting functions to actual data, or else by scaling fitted functions, or by assuming costs are independent of oil output (and therefore are constant), where subscripts E, D, OED and P refer to exploration, development, other exploration and development, and production. C_{OED} is a constant.

Q = oil output in million barrels per day

Each marginal cost is estimated separately as a function of oil output based on data available from American Petroleum Institute and EIA.

6.2.4.1.1 MEC AND MDC

This section estimates MEC and MDC with costs of drilling and equipping wells by depth intervals from the JAS. We employ an exponential function to characterize MEC and MDC.

It makes economic sense that the shallowest oil wells, which are the lowest cost, are explored and developed first, followed by less shallow ones, and lastly the deepest. The median cost per well, not affected by very high or low values, is chosen for our analysis because it is a better representation of the central tendency of the population than the average cost per well. We create a new variable “cumulative number of wells” for each well depth interval by adding up the number of wells with depth interval no more than its upper limit, rank the median cost from the lowest to the highest, and plot the cost per well in thousand dollars against cumulative wells shown in Figure 6-3. Costs are adjusted to constant 2005 US dollars using a GDP deflator. All costs and prices used in the dissertation are converted to constant 2005 US dollars.

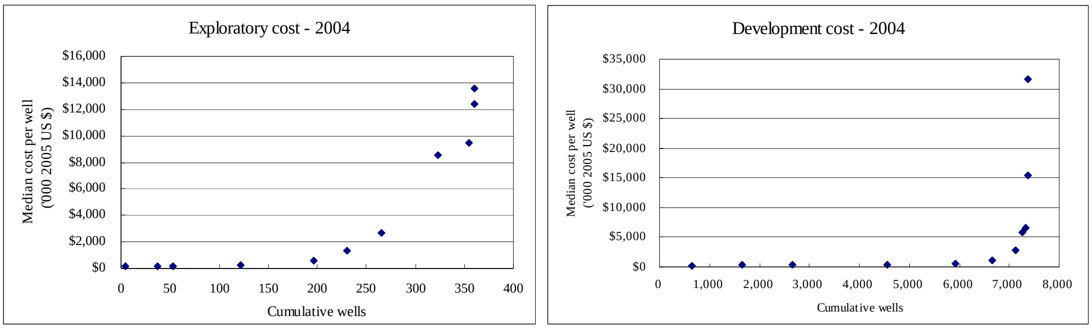


Figure 6-3 Median cost per well versus cumulative number of wells

The EIA Annual Energy Review (AER) 2008 contains information in crude oil production and crude oil well productivity for the years 1954-2008. Given the total production of 5,419 thousand barrels per day in 2004, we can calculate the average production per exploratory or development well by dividing total production by total exploratory or development wells. For each well depth interval category (from the JAS data), the number of wells and median cost per well are converted into oil production in barrels and cost per barrel separately with the following two equations. The first equation determines the production per barrel in each depth interval:

$$Q_i = W_i \times \frac{TP}{TW} \qquad (6\text{-}2)$$

where Q_i is the oil production level in barrels for depth interval i, W_i is the number of exploratory or development wells for depth interval i, TP is the total oil production, and TW is the total number of exploratory or development wells over all depth intervals. The second equation determines the cost per barrel for each depth interval:

$$C_i = (W_i \times CW_i) / Q_i \qquad (6\text{-}3)$$

Where C_i and CW_i are cost per barrel and median cost per well for the *i*th depth interval. Figure 6-4 graphs the cost in dollar per barrel against cumulative production in barrels for exploratory and development wells.

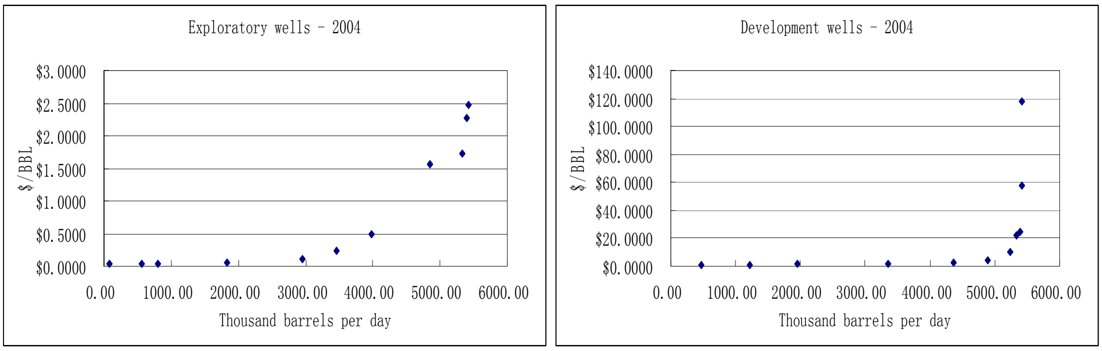


Figure 6-4 cost per barrel versus production levels

Using the above cost and production data points, we tried fitting the data to three functional forms for where *y* is the cost in $/bbl and *x* is the production level in million barrels per day (MMBD). Regression results for the three functional forms are presented in Table 6-3. Of the three, the exponential form[7] (the 3^{rd} one) is chosen for both exploratory and development wells as it provides the best goodness of fit and the coefficients are statistically significant.

[7] We also tried the quadratic form used in NEMS. For exploration cost, a function form $y=ax+bx^2$ fits the data quite well with a little better R-squared value (0.97), and coefficients are significant at 5% level (but P-value is larger than that using the exponential form). For development cost, a quadratic function doesn't fit at all and no coefficient is statistically significant.

Table 6-3 Regression results with three assumed functional forms

	Functional form	y = a + b x	ln(y) = a + b ln(x)	y = exp(a + b x)
Exploratory wells	Coefficient: a, b Standard error p-value	-0.4697, 0.4098 (0.3040) (0.0820) (0.1567) (0.0007)	-2.0698, 1.0730 (0.3936) (0.2717) (0.0005) (0.0034)	-4.0379, 0.8579 (0.2352) (0.0634) (<1E-5) (<1E-5)
	R-squared	0.735	0.634	0.953
Development wells	Coefficient: a, b Standard error p-value	-16.1807, 9.7975 (23.803) (5.5366) (0.5138) (0.1106)	-0.1038, 1.6643 (0.6684) (0.4805) (0.8800) (0.0071)	-1.2995, 0.7998 (0.7239) (0.1684) (0.1062) (0.0010)
	R-squared	0.258	0.571	0.715

Thus, we estimate marginal exploration cost (MEC) and marginal development cost (MDC) as a function of oil output (Q), shows as follows:

$$MEC = \exp(-4.0379 + 0.8579 * Q)$$

$$MDC = \exp(-1.2995 + 0.7998 * Q)$$

6.2.4.1.2 OED costs

We make some assumptions to estimate other exploration and development costs (OED) with data from the API and the EIA.

In addition to the costs of drilling and equipping wells, total exploration expenditures also include the costs of acquiring undeveloped acreage, land scouting, geological and geophysical activities, lease rental, direct overhead and general administration. Similarly, total development expenditures include the costs of lease equipment, acquiring producing acreage, improved recovery programs, direct overhead and general administration. The API provides the survey on oil and gas expenditures for exploration, development and production separately, but no recent detailed breakdown for oil only that identifies the contribution of “other” costs. Complete data for other exploration and development (OED) expenditures was available from API only for the period 1976-1982. Fortunately, the EIA Financial Reporting System (FRS) (2008) includes several schedules for review of the functional performance (financial data on energy supply) of the major U.S. energy-producing companies in total from 1977 to 2007. Both oil and gas wells are included in the FRS schedules for petroleum operations. The comparison between API and FRS data for their overlapped period (1977-1982) shows that the total OED cost from FRS was about 25%-50% of that from API with the lowest percentage in 1979. A simple regression of API total OED cost (*API_OED*) on FRS total OED cost (*FRS_OED*) generates the results as follows.

$$API\_OED = 2.67109 * FRS\_OED \qquad (6\text{-}4)$$

(0.21656) Standard Error

0.00006 p-value

R-Squared = 0.9682

We employ this coefficient to scale up the FRS total OED costs from 1983 to 2007 for estimating the API total OED costs. Total OED costs including oil and gas wells are then divided by total oil and gas production levels (EIA, 2008) to obtain the average OED costs over time, which appear to have similar pattern with oil prices over time (Greene, 2009), as shown in Figure 6-5. The comparison, to some extent, justifies our method used to project future oil costs (to be discussed in section 6.2.4.4). We make two assumptions: (1) oil and gas have the same average OED costs; and (2) the average cost is independent of oil production. The second assumption is based on the calculated correlation coefficient (less than 0.1) between average OED cost and oil production over the period 1976-2007. With these assumptions, we can add the average OED cost in 2004 as a constant (C_{OED}) to the sum of exploratory and development drilling costs.

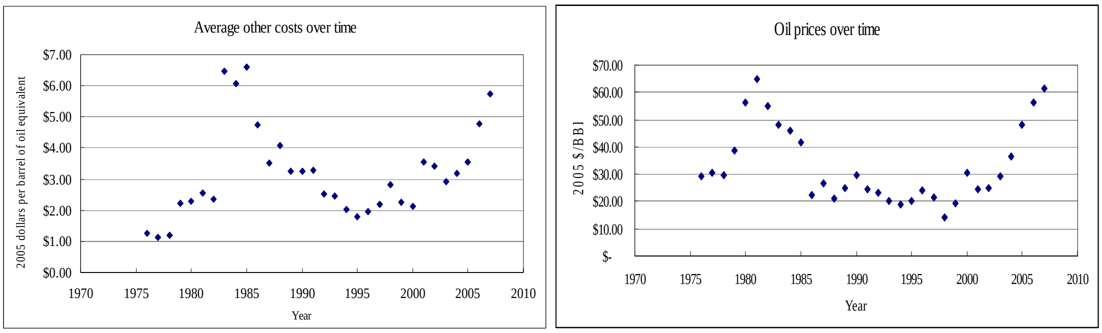


Figure 6-5 Average OEC costs and oil prices over time

6.2.4.1.3 MPC

To estimate the MPC, we assume an exponential function and calibrate it with data from the EIA/FRS.

Oil exploration and development are followed by oil production. However, we do not have current data on oil-production costs. The production cost data available from API was for annual total oil & gas production from 1973 to 1991, involving direct operating expenditures, taxes, general and administration overhead and other indirect expenses. To find out what the oil production cost curve may look like after 1991, we investigate the detailed statistics on “support activities for oil and gas operations” in the mining sector from the U.S. Economic Census (1987-2007). These statistics are available every five years from the U.S. Census Bureau. Five data sets for years 1987, 1992, 1997, 2002 and 2007 show that each cost category, including the payroll, cost of supplies, total shipments/receipts/services, total depreciation, total rents, and other expenses, increased non-linearly over time. Given that the annual oil and gas production (in barrels of oil equivalent) changed very little (17-18 MMBD) during these years, we conclude that the marginal production costs also increased non-linearly with cumulative outputs.

To simplify modeling oil marginal production cost (*MPC*) change with oil production *Q*, we assume it has a similar shape to the above drilling cost shown in functional form (6-5), where *c* and *d* are parameters to be calibrated with 2003 and 2004 data:

$$MPC = c \cdot \exp(d \cdot Q) \qquad (6\text{-}5)$$

The most recent total production costs, available from both API and FRS, indicate that the FRS costs were about 70% of the API costs. We use this ratio to scale up the FRS total production costs in 2003 and 2004. Total production cost and oil and gas production in 2003 and cumulative production cost and production in 2003 and 2004 are the two data sets[8] used to estimate the coefficients *c* (=2.9332) and *d* (=0.006971).

The sum of all the costs incurred to oil supply yields the total oil supply cost curve shown in Figure 6-6. Assuming that the domestic oil industry is perfectly competitive, the oil supply curve is the same as the oil marginal cost curve. Total U.S. oil

[8] Here two equations are used for solving two unknowns (c and d).

production including lease condensate in 2004 was 5.419 MMBD and oil price was $36.68/bbl (Greene, 2009). According to our estimated oil supply curve, the corresponding marginal cost was $28.85/bbl, and this may indicate that the US oil market has some markup. The US oil producer surplus fraction (PSf) of total prices-times-quantity payments in 2004 is about 69%, calculated using equation (6-6). The average oil cost is $11.29/bbl, calculated with the integral of the marginal cost curve from 0 to 5.419 MMBD divided by the oil production.

$$PSf = 1 - \frac{\int_0^{Q_0} MC(Q)dQ}{P_0 * Q_0} \qquad (6\text{-}6)$$

Where $MC(Q)$ is the marginal cost of oil for the US in 2004, and the complete function form (each item corresponds to that in equation 6-1) is as follows:

$$MC(Q) = \exp(a_1 + b_1 \cdot Q) + \exp(a_2 + b_2 \cdot Q) + C_{OED} + c \cdot \exp(d \cdot Q)$$

Oil marginal cost = Exploration + development + “other costs” + production (6-7)

Parameters a_1, b_1, a_2 and b_2 are estimated in Table 6-3 (column 5).

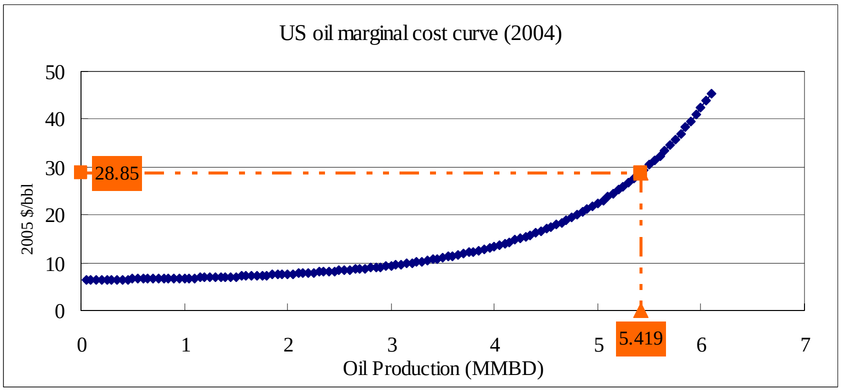


Figure 6-6 US oil supply curve in 2004

Ideally, we would estimate the oil supply curves for OPEC and ROW separately using the similar method. However, the API JAS data does not include detailed drilling cost data for other regions. Although the FRS data contains total oil costs for other foreign regions, including Canada, OECD Europe, Africa, Middle East, FSU & East Europe, and other Western and Eastern Hemispheres, the cost data was incomplete for some regions and expenditures on oil wells and gas wells were not distinguishable. Furthermore, FRS covers major energy-producing companies only. We'll treat OPEC and ROW differently with data from World Bank in Section 6.2.4.3.

6.2.4.2 Current US gasoline supply curve

In this section, we make one assumption about the correlation between oil costs and gasoline costs to derive gasoline supply cost.

Oil and gasoline prices in the US (EIA AER, 2008) have highly positive correlation shown in Figure 6-7 (gasoline prices shown here exclude taxes). Regression of gasoline price (*Pg*) in $/gal on oil price (*Po*) in $/bbl and constant is presented as follows.

$$Pg = 0.3443 + 0.0312\ Po \qquad (6\text{-}8)$$

	0.0212	0.0007	Standard Error
	<0.00001	<0.00001	p-value

Unadjusted R-squared = 0.992749

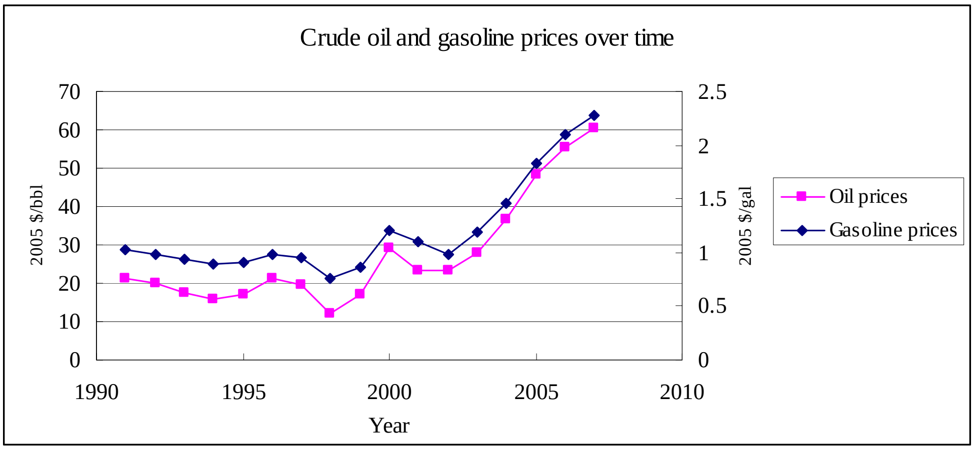


Figure 6-7 Crude oil domestic first purchase price and motor gasoline refiner sales prices

The US total oil cost has been estimated as a function of oil output, and historical oil and gasoline prices appeared to have strong correlation. To derive the US gasoline cost curve, we assume that oil and gasoline marginal costs (MC_o and MC_g) have the same correlation as their prices, i.e. $P_g = a + bP_o$ and $MC_g = a + bMC_o$, where a and b are coefficients in Equation 6-8. This assumption allows that the derived gasoline cost curve includes both oil supply and refinery costs.

A barrel is equivalent to 42 gallons. At a typical U.S. refinery, roughly 47% of its crude oil input is finished gasoline although the conversion factor varies from refinery to refinery (Transportation Energy Data Book, Edition 28, Newton BBS). Based on this average, one barrel of oil is assumed to produce 19.74 gallons of gasoline and we use this for the quantity conversion from crude oil to gasoline. Gasoline marginal cost (MC_g) as a function of gasoline output (Q_g in million gallons per day) is presented as follows. The estimated US gasoline marginal cost curve is shown in Figure 6-8.

$$MC_g = a + b \cdot [\exp(a_1 + b_1 / 19.74 \cdot Q_g) + \exp(a_2 + b_2 / 19.74 \cdot Q_g) + C_{OED} + c \cdot \exp(d / 19.74 \cdot Q_g)]$$

According to EIA AEO 2007, gasoline price in 2004 was $1.952/gal. Highway Statistics 2004 gives the weighted average tax rate on motor gasoline as 37.65 cents per gallon. The pretax gasoline price in 2004 therefore was 1.952-0.3765= $1.58/gal (red line). Recall that the crude oil production in 2004 was 5.419 MMBD (EIA, 2008), which may produce about 107 million gallons of gasoline per day[9] (green line) with 47% conversion factor. The producer surplus associated with domestic gasoline fuel is the area bounded by price line and marginal cost curve from output level zero to 107 (estimated gasoline output in 2004 from domestic oil).

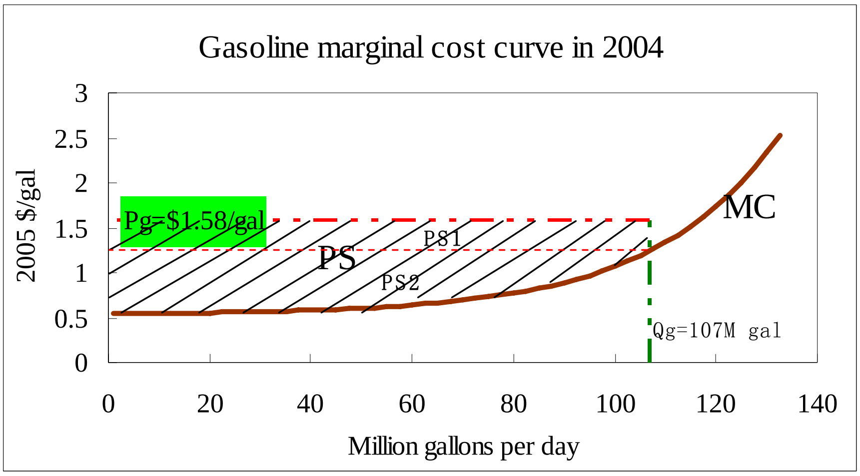


Figure 6-8 US gasoline cost curve in 2004

The calculated producer surplus is about 56% of total price-times-quantity payments, which includes both oil production and refinery industries. This PS fraction is lower than that oil PS fraction (69% from Figure 6-6), which follows from our assumption

9 This is an estimated US gasoline output from domestic oil in 2004 for producer surplus calculation.

about the relationship between oil prices/costs and gasoline prices/costs given the actual data[10]. This is reasonable because the downstream refining and marketing industries do not have a large difference between the resources required to refine a low-quality barrel of oil and the resources to refine a high-quality barrel of oil. We may break the producer surplus into two components: one related to the steepness of the supply curve (the area PS2, about 61.6%), and the other related to the price being higher than it should be (the area PS1, about 38.4%) due to the scaling up of oil price/MC gas (our assumption to derive gasoline cost). The possible explanation may be imperfect market in the oil and refinery industry or underestimated costs. PS1 is the rectangle area below the gasoline price and above the marginal cost ($1.24/gal) at Q_g, and PS2 is the area below the marginal cost ($1.24/gal) and above the marginal cost curve.

The area under the gasoline cost supply (total gasoline cost) is about $74.5 Million per day while the area under the oil cost curve in Figure 6-6 (total oil cost) is about $61.2 Million per day (about 47% is for gasoline). To estimate the PS in the refining industry only, we assume that the revenue to the refining industry is the revenue difference between gasoline and oil, and the cost to the refining industry is the cost difference between gasoline and oil. We calculate the PS fraction in the refining industry is 39.6%, much lower than that in the oil industry.

[10] Suppose oil PS is a, total oil cost plus PS is b, PS in refinery only is c, and total refinery-only cost plus PS is d, then oil PS fraction is a/b, and refinery-only PS fraction is c/d. Further suppose that a/b>c/d. It is easy to prove that a/b>(a+c)/(b+d)>c/d.

We have estimated the average PS for all current gasoline consumption for estimating the average cost. Next we are going to estimate two different kinds of PS ($\triangle PS_t$ and PSf_{ac}) as a result of consumption change (these are different from the above PS1 and PS2). $\triangle PS_t$ is calculated with equation 6-9.

$$\Delta PS_t = [(P_g^0 * Q_g^0) - \int_0^{Q_g^0} MC(Q_g)dQ_g] - [(P_g^* * Q_g^*) - \int_0^{Q_g^*} MC(Q_g)dQ_g] \quad (6\text{-}9)$$

Where P_g^0 = the before-change gasoline price, P_g^* = the after-change gasoline price, Q_g^0 = the before-change gasoline quantity, Q_g^* = the after-change gasoline quantity at the new equilibrium (shown in Figure 6-9), and $MC(Q_g)$ = marginal cost function of gasoline MC_g . We break the total PS change (ΔPS_t) into two pieces: one (we call this component $\triangle PS_{t,c}$) is due to the equilibrium consumption change (relevant to social cost calculation) and the other (the second component is called $\triangle PS_{t,i}$) is due to the change in price (“inframarginal” consumption, relevant to a calculation of the US cost for imported oil), shown as the following equations:

$$\Delta PS_t = \Delta PS_{t,c} + \Delta PS_{t,i}$$

$$\Delta PS_{t,c} = [(P_g^0 * Q_g^0) - \int_0^{Q_g^0} MC(Q_g)dQ_g] - [(P_g^0 * Q_g^*) - \int_0^{Q_g^*} MC(Q_g)dQ_g]$$

$$\Delta PS_{t,i} = (P_g^0 - P_g^*) * Q_g^*$$

The only unknown is the after-change gasoline price P_g^*. To estimate this, we employ the oil demand function used in NEMS (EIA, 2010), shown in Equation 6-10, and make a hypothesis that the US oil market behaves competitively. Figure 6-9 (D=demand) illustrates two supply-demand equilibrium cases before and after oil demand contracts, where MC (supply curve S) has the same shape as we estimate for 2004 (Figure 6-6), but vertically shifts up so that the curve passes through the point (P_0, Q_0), and intersects the original demand curve D at A. When oil demand declines from Q_0 to Q' (for a 10% reduction in gasoline use, $Q_g^{'} = (1-10\%) * Q_g^0$), new demand curve D' will pass through point N (P_0, Q'), but with the same demand elasticity as the initial demand curve D.

$$Q_d = \alpha \cdot P^{\varepsilon_d} \qquad (6\text{-}10)$$

Where P is the price, Q_d is the demand quantity, ε_d is the demand elasticity, -0.11, from NEMS, and α is a constant to be determined by a point on the curve.

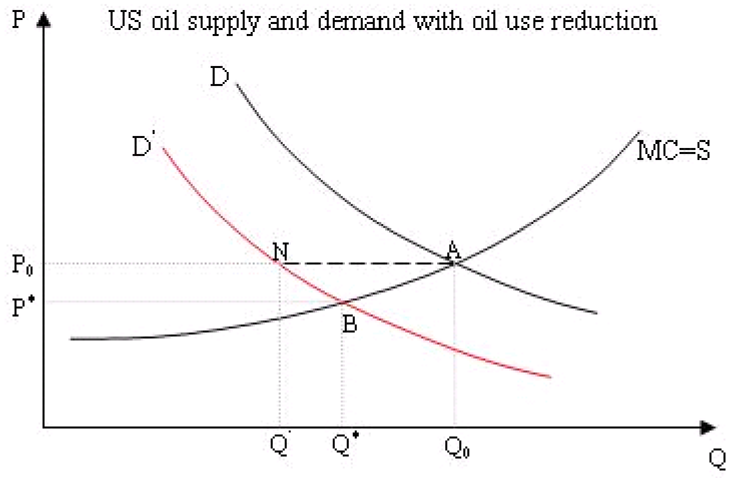


Figure 6-9 US oil market in 2004 (P_0=$36.68/bbl and Q_0=5.419MMBD)

The new demand curve D' intersects the supply curve S at B, corresponding to a new, lower price P^* (and, incidentally, to a quantity Q^* greater than Q', on account of the lower price spurring additional consumption). Based on equations 6-7 and 6-10, we estimate the after-change oil price P_o^*=$30.01/bbl for a 10% reduction in oil demand.

Plugging into equation 8, we obtain the after-change gasoline price P_g^*=\$1.28/gal. With equation 6-9, we calculate the total PS reduction ΔPS_t=\$12B, in which $\triangle PS_{t,c}$ =\$1.4B and $\triangle PS_{t,i}$=\$10.6B.

The other kind of PS (PS_{ac}) is based on the initial change in consumption due to the change in the demand curve, as shown in equation 6-11 (expressed as a fraction of P·△Q). We estimate that this PS fraction over a 10% reduction in gasoline use (PSf_{ac}) is 29.9%. So the average cost $AC=P\cdot(1-PSf)$ as a fraction of price P is 70.1%.

$$PSf_{ac} = \frac{\Delta PS}{P_g^0 \cdot \Delta Q_g} = \frac{[P_g^0 Q_g^0 - \int_0^{Q_g^0} MC(Q_g)dQ_g] - [P_g^0 Q_g^{'} - \int_0^{Q_g^{'}} MC(Q_g)dQ_g]}{P_g^0 \cdot (Q_g^0 - Q_g^{'})} \quad (6\text{-}11)$$

As the consumption reduction increases, the PS fraction will get bigger due to the steepness of the supply curve. However, the PS per gallon from the changes in consumption and price (equation 6-9) will get smaller as the consumption reduction increases because consumer gains from the price drop.

6.2.4.3 Current world oil supply curve

To estimate PS for OPEC and the rest of the world, we start with unpublished World Bank data on crude oil to develop oil supply cost curves for OPEC and ROW (the Rest of the World except the US). The World Bank data contains annual oil production, rent and average world price for many countries from 1970 to 2004, including nine OPEC members such as Iraq, Iran, Kuwait, Sandi Arabia and so forth.

An exponential function form with two parameters similar to equation (6-5) is assumed for OPEC and ROW marginal cost curves. One country's total oil cost for each year is calculated with world oil price times the country's oil output minus the country's oil rent[11]. The sum of total oil costs for the nine OPEC members gives the total OPEC oil cost and the sum of total oil costs for the rest countries (except the US) gives the total ROW oil cost. We calibrate the exponential curve with the most recent data (years 2003 and 2004) for OPEC and ROW separately, and then obtain the following functions[12]:

$$MC_{OPEC} = 2.19 * \exp(0.0024 * Q_{OPEC}) \qquad (6\text{-}12)$$

$$MC_{ROW} = 9.02 * \exp(0.00048 * Q_{ROW}) \qquad (6\text{-}13)$$

where Q is in billion barrels and MC is in constant 2005 US dollars per barrel.

The oil marginal cost curves for OPEC and ROW in 2004 are shown in Figure 6-10 that oil marginal cost for OPEC is less than one-quarter of that for ROW. It appears that the two curves are linear because the exponents in the equations 6-12 and 6-13 are close to zero. We provide two more detailed view graphs for OPEC and ROW but with different y-axes. Compared to the US oil cost curve in Figure 6-6, OPEC has a much lower marginal cost and the cost increase with output level is very little, i.e. the marginal oil cost of OPEC is quite inelastic with respect to its output. According to the World Bank data, OPEC oil output in 2004 was about 22.63 MMBD with average cost of $2.3/bbl and ROW oil output in 2004 was about 40.08 MMBD with average

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[11] Here the oil rent is derived by the product of oil output and the difference between oil price and average oil cost, and this is different from the economic rent discussed in Section 6.2.1.

[12] This is similar to our estimate for US oil production marginal cost (MPC) in Section 6.2.4.1.3.

cost of $9.2/bbl. In contrast, our estimate for the corresponding marginal cost is $2.24/bbl for OPEC with equation 6-12 and $9.08/bbl for ROW with equation 6-13. Given the world oil price at about $37/bbl in 2004, OPEC would earn a large amount of producer surplus. To shed some light on the foreign producer surplus, we provide some rough calculations of producer surplus from OPEC and ROW in 2004 as compared to the US results.

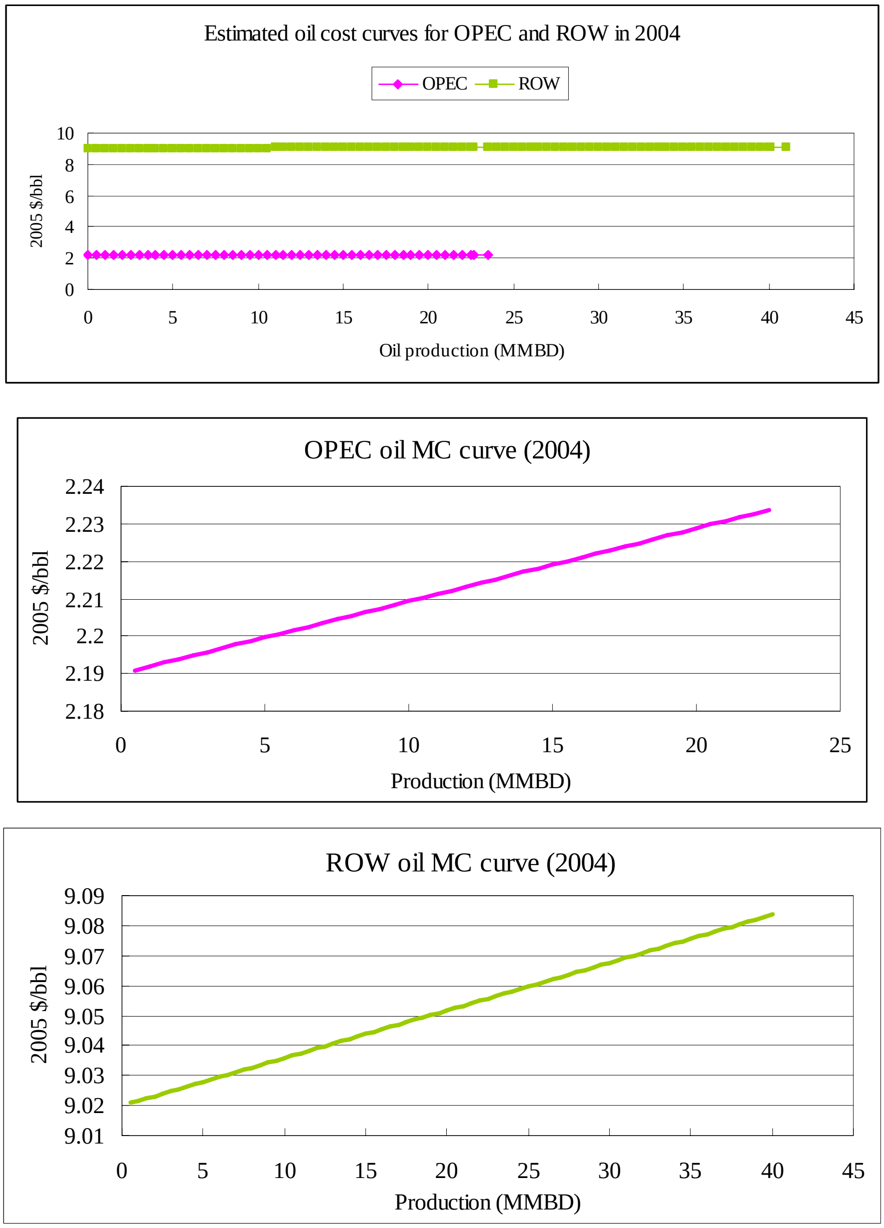
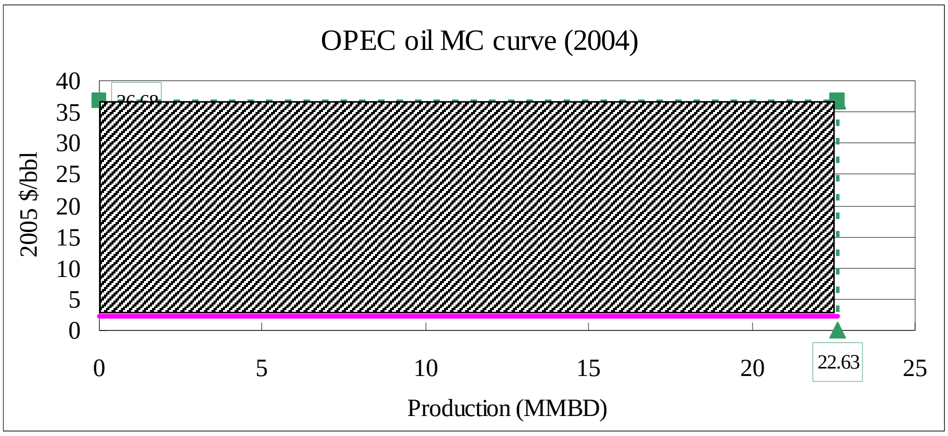


Figure 6-10 Oil supply cost curves for OPEC and ROW

Given the 2004 oil price P^0 ($36.68/bbl), the oil producer surplus fraction of total price-times-quantity payments is about 94% for OPEC and about 75% for ROW as shown in Figure 6-11 (shaded areas). This amounts to $34.4/bbl for OPEC and $27.6/bbl for ROW. By contrast, the US oil producer surplus fraction in 2004 is about 69% (Figure 6-6). Comparing the magnitudes[13], the total OPEC producer surplus associated with total OPEC production in 2004 is $285 billion, which is more than five times the total US producer surplus associated with total US oil production, $49 billion. According to the recent data from EIA FRS (2008), total cost (acquisition, exploration, development and production) incurred for petroleum operations increased sharply from 2004 to 2008 for the US and foreign producers. Particularly, the 2008 petroleum expenditure in the Middle East is more than three times the 2004 one. As oil price was also rising rapidly, the trend for producer surplus fraction is very uncertain beyond 2004.



[13] This comparison is for the oil industry only and refinery is not considered.

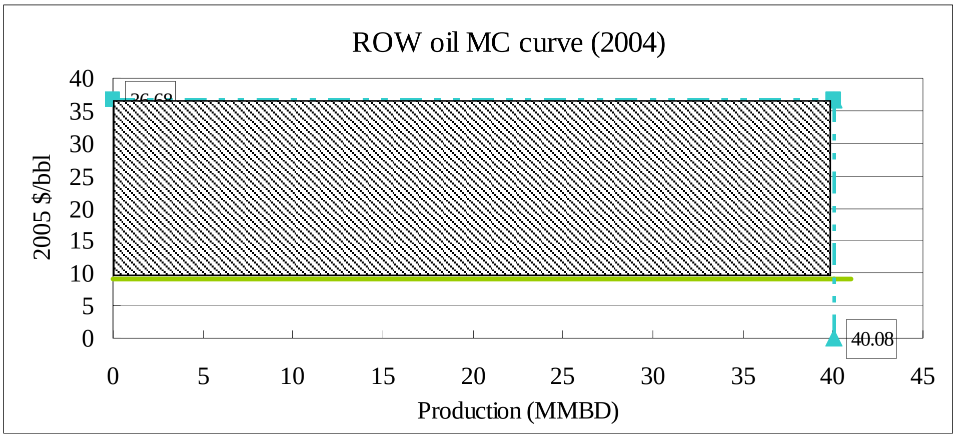


Figure 6-11 Oil producer surplus calculation for OPEC and ROW

With the estimated PS to the US refinery only in section 6.2.4.2, we can estimate the total gasoline PS fraction with imported oil from OPEC or ROW. Table 6-4 summarizes all the PS fractions in 2004 for oil industry in the US, OPEC and ROW, for US refinery industry, and for the total gasoline cost given three different combinations (US oil + US refining, OPEC oil + US refining, and ROW oil + US refining). For the US, the total gasoline PS fraction for imported oil is much higher than that for domestic oil.

Table 6-4 Summary of all the PS fractions in 2004

Oil industry	US	69%
	OPEC	94%
	ROW	75%
US refinery	US	40%
Total gasoline (oil + refinery)	US oil + US refinery	56%
	OPEC oil + US refinery	89%
	ROW oil + US refinery	73%

How much would producer surplus decrease when oil demand reduces by 10% for OPEC and ROW as compared with the US? To answer the question, we should first estimate the world oil price P^c after the oil demand change, which depends on our view of the world oil market. If we assume it is a competitive world market, then P^c equals marginal cost (MC*) where the MC* at Q* (quantity after the change) is determined by the "world" long-run MC function. If we assume that OPEC simply maintains price, then P^c equals P^0. Any assumptions between MC* and P^0 are possible. We derive the "world" oil cost curve shown in Figure 6-12 with data from the World Bank using the same method as OPEC and ROW oil cost curves. Equation 6-14 describes our derived hypothetical "world" marginal cost, which depicts world short-run cost curve in 2004. The "world" oil marginal cost is about $7.58/bbl, much lower than oil price. If the "world" oil cost curve is believable to some extent, then we can conclude that the world oil market is not perfectly competitive, most likely due to OPEC behavior. To formally model OPEC behavior is beyond the scope of this analysis, and will be addressed in the future research. We assume the ratio P^c/P^0 is the same as the ratio of MC when oil demand reduces by 10%, i.e. the "gap" (P-MC) in the "world" oil market remains the same as before. Thus we obtain the P^c=P1 that is $36.22/bbl, slightly lower than the world oil price in 2004.

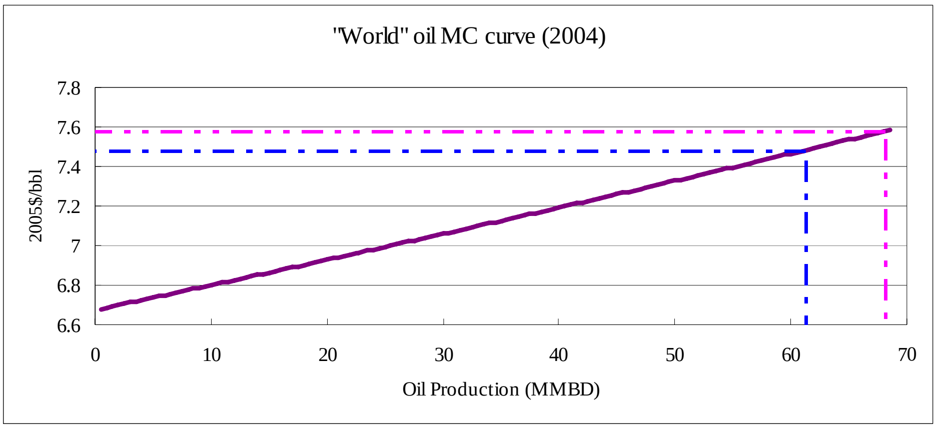


Figure 6-12 "World" oil cost curve

$$MC_{world} = 6.6743 * \exp(0.0051 * Q_{world}) \quad (6\text{-}14)$$

For a 10% reduction in oil use ($\triangle Q_o$), the total PS reduction $\triangle PS_t$ for OPEC expressed as $/bbl ($\triangle PS_t / \triangle Q_o$) is $38 where $\triangle PS_{t,c}$ per barrel is $34, higher than ROW and US, and $\triangle PS_{t,i}$ per barrel is $4. OPEC's PS fraction PSf_{ac} over the 10% oil use reduction is 92.6%, higher than ROW's which is higher than the US. However, the after-change oil price P^c could be the same as P^0 if OPEC's strategy is to remain oil price. In this case, OPEC's total PS reduction per barrel will be $4 less, but is still higher than the US amount ($12). Table 6-5 presents the result of two different kinds of producer surplus change for 10%, 20% and 50% oil use reductions under three cases to examine the sensitivity to P^c and therefore to assumptions about OPEC market power. The range of prices we examine spans perfect competition to OPEC market power. Case 0: P^c=P*=MC* (this is not likely according to the World Bank data); case 1: P^c=P2, mean of P^0 and MC*; case 2: P^c=P1 where the ratio of price and marginal cost remains constant; case 3: $P^c=P^0$, the same price as before.

Table 6-5 Oil producer surplus change associated with different prices after 10%, 20% and 50% reductions in oil consumption

Oil use reduction		Case 1			Case 2			Case 3		
		$\triangle PS_t$ ($/bbl)		PSf_{ac}	$\triangle PS_t$ ($/bbl)		PSf_{ac}	$\triangle PS_t$ ($/bbl)		PSf_{ac}
		$\triangle PS_{t,c}$	$\triangle PS_{t,i}$		$\triangle PS_{t,c}$	$\triangle PS_{t,i}$		$\triangle PS_{t,c}$	$\triangle PS_{t,i}$	
10%	P^c	P^c=$22.08/bbl			P^c=$36.22/bbl			$P^c=P^0$=$36.68/bbl		
	OPEC	34.0	131.4	92.6%	34.0	4.1	92.6%	34.0	0	92.6%
	ROW	27.0	131.4	73.6%	27.0	4.1	73.6%	27.0	0	73.6%
	US	12.1	131.4	33.0%	12.1	4.1	33.0%	12.1	0	33.0%
20%	P^c	P^c=$22.04/bbl			P^c=$35.76/bbl			$P^c=P^0$=$36.68/bbl		
	OPEC	34.2	58.6	93.3%	34.2	3.7	93.3%	34.2	0	93.3%
	ROW	27.3	58.6	74.4%	27.3	3.7	74.4%	27.3	0	74.4%
	US	15.4	58.6	41.9%	15.4	3.7	41.9%	15.4	0	41.9%
50%	P^c	P^c=$21.90/bbl			P^c=$34.42/bbl			$P^c=P^0$=$36.68/bbl		
	OPEC	34.4	14.8	93.7%	34.4	2.3	93.7%	34.4	0	93.7%
	ROW	27.5	14.8	74.9%	27.5	2.3	74.9%	27.5	0	74.9%
	US	21.3	14.8	58.0%	21.3	2.3	58.0%	21.3	0	58.0%

Table 6-5 shows that for case 1 (lower oil price), $\triangle PS_{t,c}$ per barrel increases slightly while $\triangle PS_{t,i}$ decreases sharply with the increase in oil use reduction. The best scenario under case 1 for producers is 50% reduction in oil use because the PS reduction is the lowest. However, with the same reduction in oil use, $\triangle PS_{t,i}$ per barrel decreases as after-change price increases. Specifically, OPEC's constraint on oil output forces high-cost supply onto the market and then the world oil price goes up. These high-cost producers partially fill in the supply reduction by OPEC. OPEC's short-run strategy is to maximize PS by finding the optimal output that maximizes their revenue, when the benefit from the higher price no longer more than compensates for the reduced sales. OPEC'S long-run strategy is more complicated as they do not want to maintain high prices for so long that consuming countries begin to take long-run oil conservation measures. For the three possible P^c values (cases 1-3), OPEC has more producer surplus reduction per barrel than ROW that has more producer surplus reduction than the US due to reduced oil consumption. Therefore, oil consumption contraction would have more impact on foreign producers than on US producers.

In terms of the change in PSf_{ac}, all producers (OPEC, ROW and US) benefit from oil use reduction because average cost as a fraction of price decreases with the increase in oil use reduction (PSf_{ac} gets bigger with the increase in oil use reduction). Particularly, the US gains the most from oil use reduction (the increase in PSf_{ac} is the largest).

6.2.4.4 Future Oil and Gasoline Marginal Cost

In this section, we estimate the future oil marginal cost curve and then the future gasoline marginal cost for the US based on the historical data and our estimated 2004 US oil marginal cost curve. As API or FRS does not provide cost data for oil wells and gas wells respectively, we first try to model the total cost (TC, including both oil and gas wells) as a function of time (t), oil price (Poil), oil output (Qoil), gas output (Q_{gas}) and remaining reserves (Rev) of oil and gas, as given in Equation 6-10. Assuming oil and gas have the same average cost, we then estimate average oil cost. To obtain the future oil marginal cost curve, we shift the 2004 US oil cost curve so that the curve produces the same average oil cost as we estimate. Finally, gasoline marginal cost curves are derived with the same method as stated in Section 6.2.4.2.

$$TC = f(t, P_{oil,} Q_{oil}, Q_{gas}, \mathrm{Re}\,v) \qquad \text{(6-15)}$$

The EIA AEO 2009 presents projections on US energy supply, demand and prices through 2030 under five cases: reference, high price, low price, high economic growth and low economic growth. The lower 48 crude oil wellhead price in 2030 is projected to be $45/bbl under low price case (oil output: 5.36 MMBD) and $194/bbl under high price case (oil output: 8.47 MMBD). US future oil cost may have a variety of influencing factors, including geopolitics, technological progress, oil output, world oil price, remaining reserves, investors' strategy, and alternative energy options. For simplification, we select time, oil price, oil output, gas output and remaining oil & gas reserves as possible explanatory variables to fit the historical cost data from API and FRS, and choose the best-fitting one for estimations.

The total cost incurred to extract and produce petroleum sources includes expenditures on acquisition, exploration, development and production. The historical total cost data from API and FRS for the period from 1977 to 1991 indicates that the FRS total cost was about 70% of the API total cost. We extrapolate the API total cost by dividing the FRS total cost by 0.7 for the years 1991-2007. Thus we have total cost (*tc*) available over years 1977 - 2007. For each case in EIA AEO 2009, a new variable "Price Difference" is generated by the annual oil price minus the average oil price over the years 1977-2030.[14] The variable "Price Difference" is labeled as "*Pdiff*" under the updated reference case, "*PdHP*" under the high-price case, "*PdLP*" under the low-price case, "*PdH*" under the high-economic growth case, and "*PdL*" under the low-economic growth case. Remaining oil and gas reserves (beginning-of-year) in 2007 are estimated by adding the 2007 oil and gas production to the 2007 end-of-year

[14] We are interested in the oil cost curves beyond 2004, and EIA AEO 2009 provides projections till 2030.

oil and gas reserves. For the period from 1977 to 2006, the beginning-of-year reserves are calculated backward. We take the natural logarithm of the total cost as the dependent variable and try different combinations of the five variables (time, oil production, gas production, price difference and natural logarithm of reserves) as regressors. Regression results show that coefficients on oil production and price difference are statistically significant at 5% level and the coefficient on gas production is not statistically significant even at 10% level. According to this, we can assume that total cost is independent of gas production. In theory, annual total cost should decrease with time (technological progress effect), increase with annual oil output (supply Q_{oil}), and increase with decreasing reserves (exhaustible resource depletion). We screen out unreasonable results that are against the theory and finally choose oil output and price difference as two dependent variables for regression of total cost under the five cases shown in Table 6-6. The regression shows that the coefficients on oil output and price difference are the same across the five cases and the only difference is the constant. So we present the reference case for estimating the future oil marginal cost curve.

Table 6-6 Regression of natural logarithm of total cost on oil output and price difference (using data from 1977 to 2007)

	Ln(tc)	Coefficient	Std Error	T stat	p-value
Reference (Ref)	Const	4.63619	0.196944	23.541	<0.00001
	Q_{oil}	0.0608783	0.025359	2.401	0.02325
	Pdiff	0.0280192	0.00221783	12.634	<0.00001
	R-squared = 0.861248				
High-price (HP)	Const	5.35112	0.225303	23.751	<0.00001
	Q_{oil}	0.0608783	0.025359	2.401	0.02325
	PdHP	0.0280192	0.00221783	12.634	<0.00001

	R-squared = 0.861248				
Low-price (LP)	Const	4.08316	0.184167	22.171	<0.00001
	Q_{oil}	0.0608783	0.025359	2.401	0.02325
	PdLP	0.0280192	0.00221783	12.634	<0.00001
	R-squared = 0.861248				
High-Econ (HEN)	Const	4.74928	0.200636	23.671	<0.00001
	Q_{oil}	0.0608783	0.025359	2.401	0.02325
	PdH	0.0280192	0.00221783	12.634	<0.00001
	R-squared = 0.861248				
Low-Econ (LEN)	Const	4.67016	0.198018	23.585	<0.00001
	Q_{oil}	0.0608783	0.025359	2.401	0.02325
	PdL	0.0280192	0.00221783	12.634	<0.00001
	R-squared = 0.861248				

The functional form of total cost for the reference case is shown as equation 6-16. Figure 6-13 shows the predicted (fitted) versus historical total cost against time for the reference case. The regression appears to reflect the general trend of total cost. To obtain the average oil cost, we assume that oil average cost is the same as gas average cost. Predicted total annual cost beyond 2007 divided by total annual oil and gas output produces predicted annual average oil cost shown in Figure 6-14, which closely follows the oil price projections (EIA AEO 2009 reference case) and is consistent with the period-average average cost. In the high price case, EIA-projected U.S. crude oil production after 2008 is higher than in the reference case mostly because of increased production from onshore CO_2–enhanced oil recovery projects and offshore deepwater projects. Such information about changing composition of producing well types is not built in our regression. High oil price would also encourage unconventional oil development, which is beyond of the scope of our analysis.[15] We thus exclude the high-price case.

$$TC = \exp(4.64 + 0.061 \cdot Q_{oil} + 0.028 \cdot Pdiff) \qquad (6\text{-}16)$$

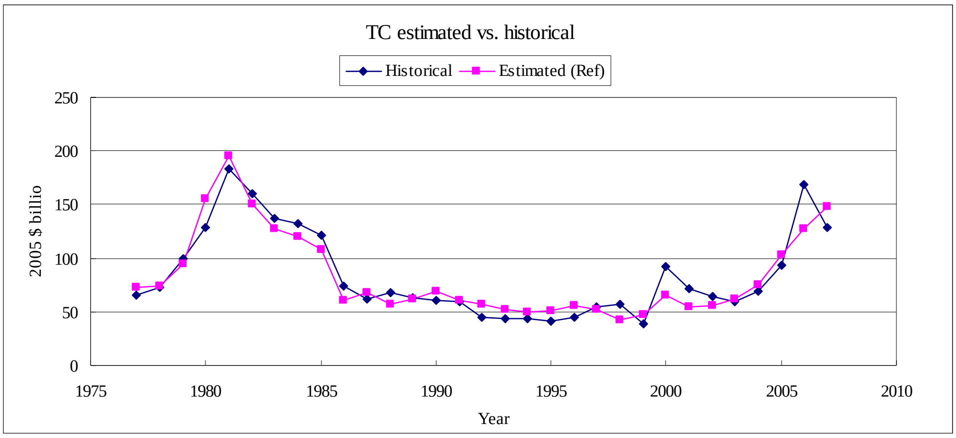


Figure 6-13 Estimated vs. actual total costs ($/year)

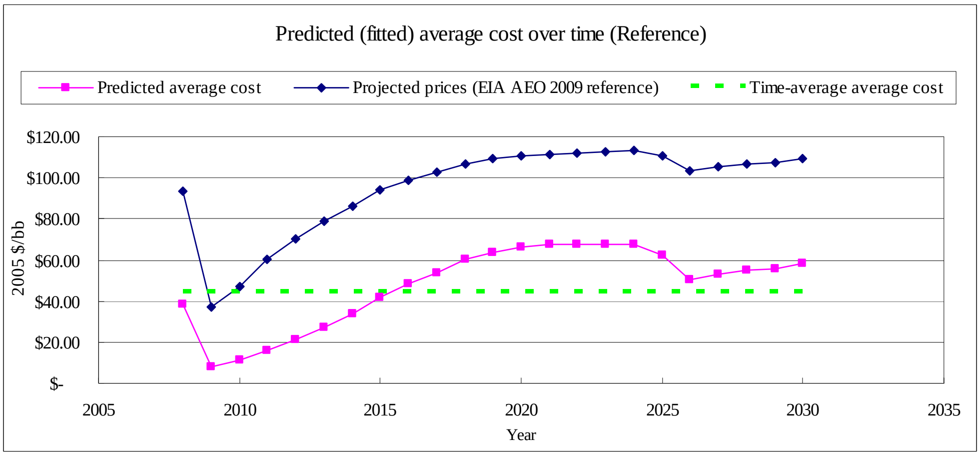


Figure 6-14 Projected oil average costs and EIA projected oil prices

According to the predicted average cost for each year, we vertically shift the 2004 oil cost curve (Figure 6-6) to make sure that the curve generates the same average cost in that particular year (integral from oil output zero to the EIA projected oil production, divided by the projected oil production). In this way, we make a simple underlying

[15] Our regression results for the high-price case show that the projected average oil cost beyond 2015 is over $200/bbl, which is even higher than EIA projected price (AEO 2009 high price case). Maybe some other factors should be included. We exclude the high-price case.

assumption that the US oil industry employs the current recovery technology in the future. To present a general trend of future oil marginal cost curve instead of many curves in different years, we take the time-average oil average cost (AC_f) for the period 2005-2030 as a proxy for estimating a single future oil marginal cost curve. The corresponding future oil production (Q_f) is just the time-average one (5.92 MMBD). The derived U.S. future oil marginal cost curve for the reference case (calculated with eq. 17) is shown in Figure 6-15, as compared with the 2004 curve (Figure 6-6). The future oil marginal cost at each output level is about $30/bbl more than the 2004 value, so the future total oil cost is much larger than that in 2004.

$$MC_f = MC_{2004} + S \qquad (6\text{-}17)$$

Where MC_f = future oil marginal cost, MC_{2004} = the 2004 oil marginal cost (equation 6-7) and S = shifter (constant value). $S = \dfrac{AC_f \cdot Q_f - \int_0^{Q_f} MC_{2004} dQ}{Q_f}$.

We conduct the regression of gasoline price on oil price and constant using the EIA projection data from 2005 to 2030 for the reference case, and then derive the gasoline cost curves assuming oil and gasoline costs have the same correlation as their prices. This is exactly the same method as we used in section 6.2.4.2, for current oil and gasoline costs. Figure 6-16 shows the estimated future gasoline cost curve in the US. Using the conversion factor that one barrel of oil produces 19.74 gallons of gasoline, we estimate the future gasoline production (116.86 million gallons per day).

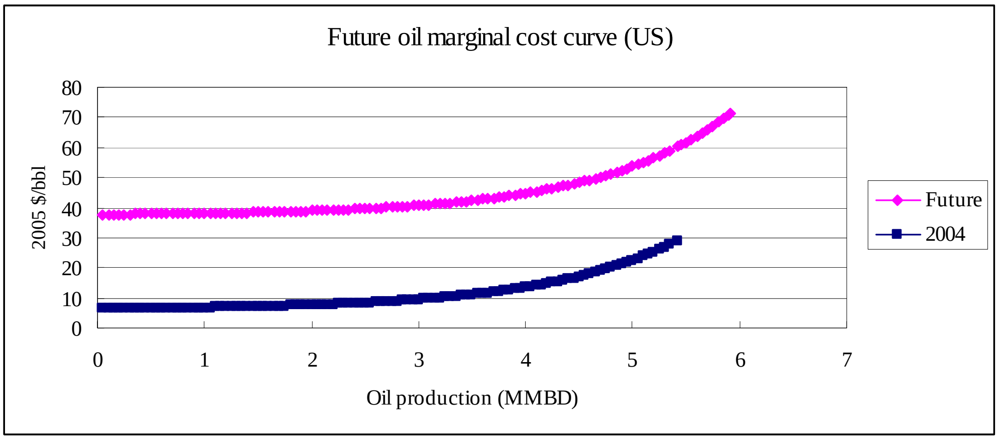


Figure 6-15 Predicted future oil marginal cost curve

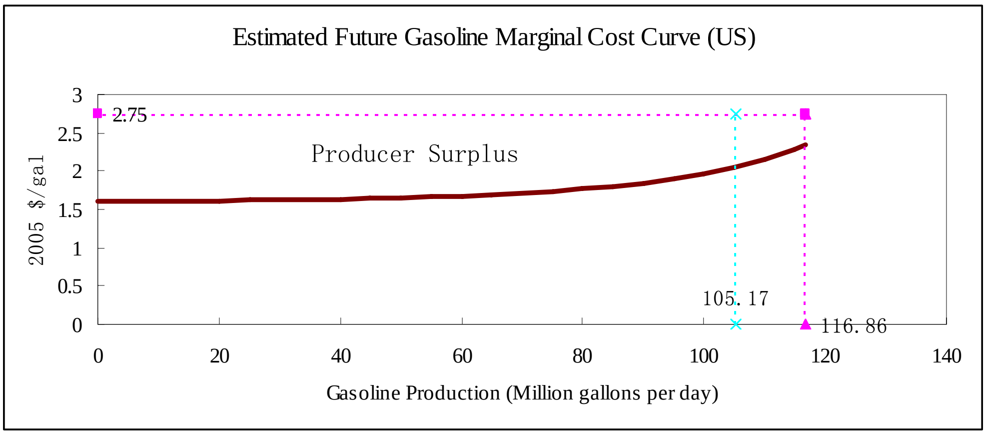


Figure 6-16 Estimated gasoline cost curves

According to our derived future gasoline cost curve including both oil recovery and refinery for the period 2005-2030, we can calculate the producer surplus that is the integral area below the gasoline price ($2.75/gal, the average gasoline price from 2005 to 2030) and above the marginal cost curve from 0 to 116.86. The producer surplus fraction with respect to price-times-quantity payments ranges is 36%, much lower than the 2004 level. This is to be expected, because we simply have shifted the cost curve up without changing its shape, which means that the cost portion of PQ payments – the area under the LRMC curve – will be larger in the future than it was in

2004.

For a 10% reduction in gasoline use, we apply the same method as the 2004 case as shown in Figure 6-9 to estimate the after-change gasoline price ($2.50/gal), and then calculate the two pieces in the producer surplus change: $\triangle PS_{t,c}$=$2B and $\triangle PS_{t,i}$ =$9.7B. The reduction in producer surplus from gasoline use contraction is a little higher for the future case relative to that in 2004 because of relatively high actual reduction in gasoline use. However, the producer surplus reduction from "inframarginal" consumption is lower than the 2004 case because of relatively small price change. The total producer surplus reduction is $11.7B, $0.7B less than the 2004 result. The PSf_{ac} over a 10% gasoline use reduction for the future case is 20.5%, less than the 2004 value, which indicates that the average cost as a fraction of price in the future would become less than the 2004 level. With future high oil cost in the US, there would be low producer surplus fraction and reducing oil demand would have less impact on the change of producer surplus fraction compared to the relatively low oil cost case in 2004.

6.2.5 Discussion

We explore the US oil cost based on the most recent data from the API JAS and projects the future US oil cost with data from the EIA AEO 2009. Based on relationships between the oil and gasoline prices, the US gasoline marginal cost is further estimated for domestic producer surplus calculation. In light of the above discussion in Section 6.2.4, the producer surplus associated with gasoline fuel that accrues to both oil producers and refiners in the US in 2004 is 56% of total price-times-quantity payments while for the period 2005 to 2030 the producer surplus fraction could reduce to 36% on average, assuming that the future supply curve has the same shape as the 2004 curve and is just shifted upward.

Table 6-7 presents the producer surplus changes ($\triangle PS_t$ in \$B including $\triangle PS_{t,c}$ and $\triangle PS_{t,i}$, and PSf_{ac}) for 10%, 20% and 50% reductions in gasoline use. As gasoline use reduction increases, $\triangle PS_{t,c}$ would increase significantly due to the steeply upward supply curve. $\triangle PS_{t,i}$ would also increase by \$4-\$5 billion as gasoline use reduction increases from 10% to 20%. Further reduction in gasoline use (from 20% to 50%) has little impact on $\triangle PS_{t,i}$ because large price drop and small actual “inframarginal” consumption” may cancel out. The PS fraction PSf_{ac} will always increase as gasoline use reduction increases. This implies that the average cost as a fraction of price in the US would decrease with the increase in gasoline consumption reduction. With the same reduction in gasoline use, the future PSf_{ac} is lower than the 2004 PSf_{ac}, which means that the future average cost as a fraction of price would be larger than the 2004 case.

Table 6-7 The US producer surplus changes for 10%, 20% and 50% reduction in gasoline use

Gasoline use reduction			10%	20%	50%
2004	$\triangle PS_{t,c}$	$B	1.4	3.5	13.2
		$/gal	0.45	0.54	0.74
	$\triangle PS_{t,i}$	$/B	10.6	15.0	15.0
		$/gal	3.45	2.30	0.84
	$\triangle PS_t$ ($/gal)		*3.90*	*2.84*	*1.58*
	PSf_{ac}		29.9%	36.2%	47.9%
Future (2005-2030)	$\triangle PS_{t,c}$	$B	2.0	5.0	17.4
		$/gal	0.55	0.65	0.86
	$\triangle PS_{t,i}$	$B	9.7	14.7	14.7
		$/gal	2.62	1.93	0.72
	$\triangle PS_t$ ($/gal)		*3.17*	*2.58*	*1.58*
	PSf_{ac}		20.5%	24.5%	31.6%

Large producer surplus on gasoline in the US implies that gasoline has a much lower social cost (to the society) than private cost (to the consumer). Alternative fuels such as hydrogen produced from renewable resources presumably do not have such difference between private cost and social cost because there exist a variety of local feedstocks and those markets probably have no opportunity for large economic rent when compared to the oil market. We'll provide an example to illustrate the hydrogen case more clearly.

Imagine that we have a national program to producer hydrogen from wind or photovoltaic electrolysis of water. Suppose half of total hydrogen supply can be produced in windy or sunny areas at a relatively low cost, while the other half must be produced in less well endowed areas at a relatively high cost. If this is a single national market, connected by some inexpensive transport modes, the hydrogen price will be set by the high-cost producers and low-cost producers will enjoy considerable producer surplus. In reality, transport costs are not negligible but moderate, and it turns out that consumers in different areas are charged at different prices that are determined by transport costs. In any give market area, the demand generally can be met by the low-cost production. If transport costs are so high that low-cost producers cannot sell in areas of high-cost production, hydrogen demand in high-cost areas will be met by local high-cost producers at a high price and in low-cost areas, demand will be met by local low-cost production. Under either the moderate or high transport costs, there is not much producer surplus for hydrogen. This is similar to the case for electricity today, where power costs vary considerably by region, and very long distance transport of power is rare.

It is noteworthy that we can estimate the average cost for some alternative fuels directly, so for these we don't have to bother with estimating producer surplus. There are two ways to estimate the economic cost: (1) build up an estimate of the average cost based on the average accounting and normal profit; or (2) subtract producer surplus from price-times-quantity revenues. For hydrogen from renewable resources, we would use the first method because there is no market for price and quantity data. In the case of gasoline, we use the second method because we have data on price-times-quantity and the gasoline price is the cost to the consumer.

From a global perspective to compare $\triangle PS_t$ for gasoline and alternatives, gasoline may be cost competitive as the large producer surplus enjoyed by OPEC members is a wealth transfer globally, not a social cost. However, the US will benefit from the producer surplus reduction due to price drop ($\triangle PS_{t,i}$) that the outflow of funds from US to OPEC will decline. In contrast to OPEC, the US will also achieve relatively large reduction in average cost (increase in PSf_{ac}) as consumption reduction increases. In addition to producer surplus, external costs of environmental impacts from petroleum-based fuel lifecycle are generally much higher than for hydrogen. This implies that developing alternative fuels with lower social cost in place of petroleum benefit those regions with plenty of domestic resources that can be easily extracted for fuel production.

6.3 Producer Surplus associated with Vehicle Purchase

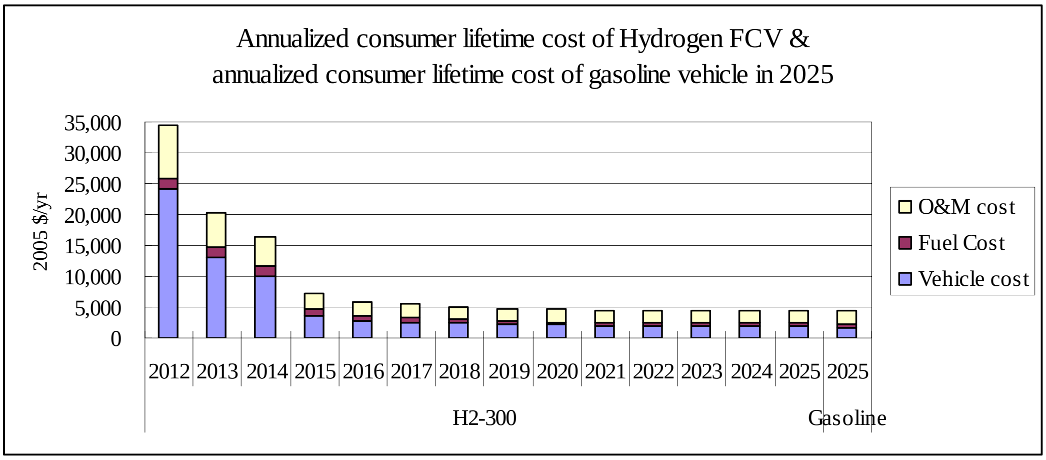
The producer surplus portion in the total payment for purchasing an automobile is estimated as the true corporate profit and is assumed to be 3% of the factory invoice price in AVCEM (Delucchi, 2006).

Chapter 7 Societal lifetime cost estimate and buy-down cost results

Based on the results in Chapters 4-6 concerning vehicle cost, fuel cost, O&M cost, valuation of externalities, and non-cost social transfers, this chapter presents the societal lifetime cost (sum of all the cost items) of a hydrogen fuel cell vehicle and compares with that of a conventional gasoline vehicle. The buy-down cost of hydrogen FCVs is finally calculated with two methods (present value and cash flow). We also perform sensitivity analysis of the buy-down cost using different oil prices and a range of external costs.

7.1 Societal lifetime cost results

The consumer lifetime cost (CLC) is the sum of the vehicle cost, fuel cost and O&M cost over the vehicle lifetime. For meaning comparison between a hydrogen FCV and a gasoline vehicle, we multiply consumer lifetime cost in cost-per-mile by annual vehicle miles traveled (VMT) for each vehicle type. The annual VMT is the same for the two vehicles, about 10,000 miles, calculated in AVCEM for gasoline vehicles. Figure 7-1 presents our estimated annualized CLC of a hydrogen FCV under DOE Scenario 3 (Figure 4-10), which shows the steepest growth in vehicle production. The annualized CLC of a conventional gasoline vehicle in 2025 is also shown here for comparison. Initially, a hydrogen FCV costs about 14 times more than a conventional gasoline vehicle, the hydrogen fuel cost is about three times of gasoline fuel cost for the first three years, and the FCV has much higher O&M cost than the gasoline vehicle (in AVCEM some O&M cost items are proportional to vehicle value such as insurance). However, as technology advances and production volume increases over time, each cost category dramatically decreases and eventually becomes cost-competitive. More importantly, the annualized lifetime hydrogen fuel cost in dollars per vehicle turns out to be much lower than for gasoline after 2019 because of the higher fuel economy of FCVs and the reduced hydrogen cost in dollars per kg, as the hydrogen supply system grows, experiencing scale economies of production and delivery. By 2025, the annualized value of FCV lifetime costs is only about $240 higher that of a gasoline vehicle. Note that while the initial vehicle cost is still higher for hydrogen, a FCV (about 17 years[16]) can last longer than a gasoline ICEV (about 15 years), and this has been considered for lifetime cost-per-mile calculations within AVCEM. The longer lifetime tends to offset the higher initial cost for FCVs.



16 In AVCEM, we assume that an ICEV's life is 150,000 miles, and the life of electric vehicles is 1.1 times the life of ICEVs because electric motors last longer than engines. With a continuous function that relates vehicle miles travelled (VMT) to age, derived from the Residential Transportation Energy Consumption Survey of the U.S. Department of Energy, the average annual VMT for an ICEV is about 10,000 miles, calculated in AVCEM. Vehicle lifetime in years is calculated with a nonlinear function that related years to miles (Delucchi, 2005). The lifetime of a hydrogen FCV turns out to be about 17 years, about 2 years longer than an ICEV.

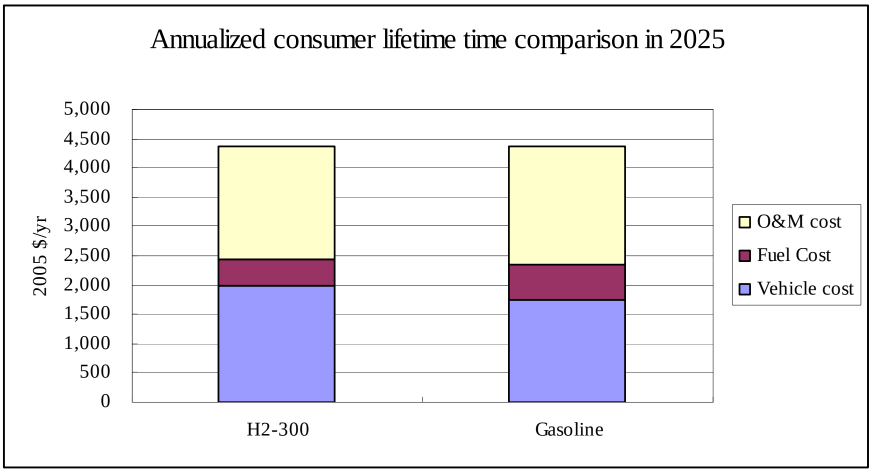


Figure 7-1 Consumer lifetime cost (present value) comparisons

Some key cost and performance information for the two vehicle options is included in Table 7-1, in which the fuel economy of gasoline vehicles is assumed to improve beyond 2006 according to the recent NRC study. The fuel economy of FCVs is calculated in AVCEM over the adjusted FUDS as shown in Figure 4-16. Compared with the NRC study, this result is more aggressive early on and less aggressive for long term. Our fuel cell vehicle retail cost results are similar to those from ORNL (Greene and Leiby, 2007), MIT (Kromer and Heywood, 2007), and the NRC (2008) (See Table 7-2).

Table 7-1 Cost and performance for gasoline vehicle and hydrogen FCV

	Gasoline vehicle	Hydrogen FCV
Vehicle retail cost*	$23,203 (remains constant over time)	$350,000 in 2012, reduced to $28,500 in 2025 by learning curve model. (Incremental cost $5,000)
Fuel economy (mpgge)	20.1 in 2006, improve 2.6% per year to 32.7 in 2025, then 1.7% increase per year to 38.8 by 2035	57.0 in 2012, 64.3 in 2015, 66.9 in 2020, 67.7 in 2025 and beyond, calculated in AVCEM based on assumed fuel cell system performance above

* Vehicle retail cost to consumer, calculated in AVCEM, is the present value of CLC of vehicle purchase, about 2.65 times OEM cost for gasoline vehicle and about 2 times OEM cost for hydrogen FCV.

Table 7-2 Comparison with other studies on fuel cell cost estimates

	Baseline gasoline vehicle	Fuel cell vehicle
ORNL	- -	DOE fuel cell target: $45/kW by 2015, $30/kW by 2020 (onboard H2 storage included) $350,000 in 2012, $56,500 in 2015, $35,000 in 2020 and $25,000 in 2025
MIT	- Fuel economy: 26 in 2006, 42.8 in 2030	OEM incremental cost compared to the 2030 gasoline vehicle: $3,600 ~ $5,100 Fuel economy (mpgge): 97 in 2030
NRC (2008)	Retail price: $23,050 constant; Fuel economy: 25.2 mpg in 2015, 42.4 mpg in 2050	Vehicle incremental retail price: from initially over $100,000 to $3,600 (learned out); Fuel economy: about 2 times that of gasoline vehicle 57.2 mpg in 2015 -> 84 mpg in 2050

To compare the vehicle options in terms of societal cost, we add external costs to and deduct non-cost social transfers from the CLC. Figure 7-2 presents the societal lifetime cost (SLC) in present value for the U.S. national accounting in the years 2012 and 2025 with medium-case external costs. The external costs are quite small compared to fuel costs and also smaller than those estimates by Ogden (2004), Lee (2009) and Thomas (2008), primarily because we assume much lower GHG damage costs, especially for the US accounting. Non-cost transfers that are to be deducted are shown below the x-axis as negative values. For conventional gasoline vehicles, about 17.5% of gasoline fuel cost is a wealth transfer from consumers to producers within the U.S, and about 38% is a transfer globally. In Figure 7-3 we actually deduct the non-cost transfers from the appropriate category to end up with what we call an adjusted cost, as follows: vehicle cost less the PS on vehicle purchase is “vehicle cost adj,” fuel cost less the PS on fuel purchase is “fuel cost adj,” and O&M cost less taxes and fees is “O&M cost adj”. As can be seen from Figure 7-3, the difference between the SLC of the hydrogen FCV and the SLC of the gasoline ICEV is greater in the global accounting than in the US accounting. This is because in the global accounting the societal cost of gasoline is less than in the US accounting, and some costs from the US perspective are non-cost transfers from a global perspective.

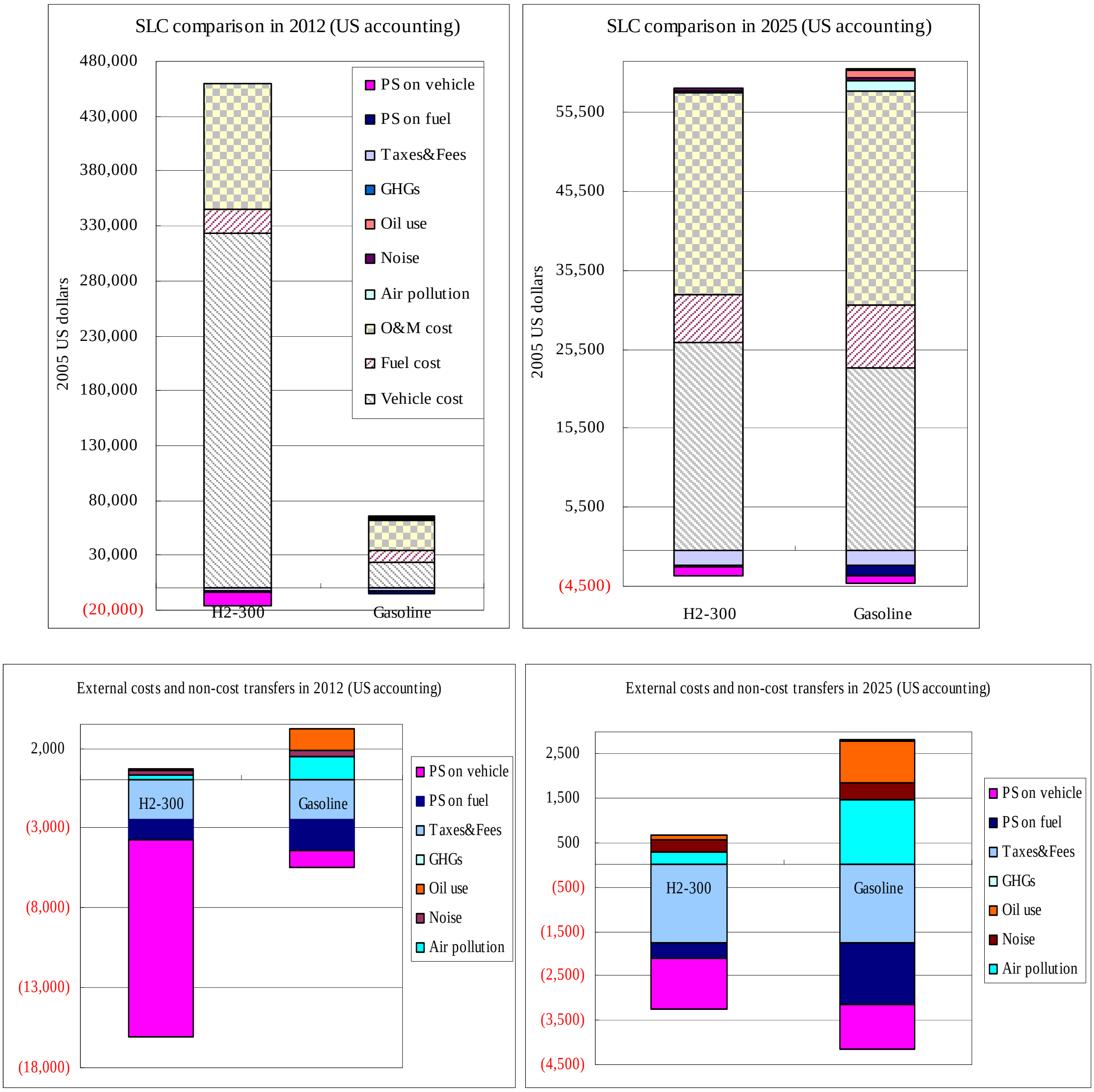


Figure 7-2 Societal lifetime cost comparison in present value (U.S. national accounting)

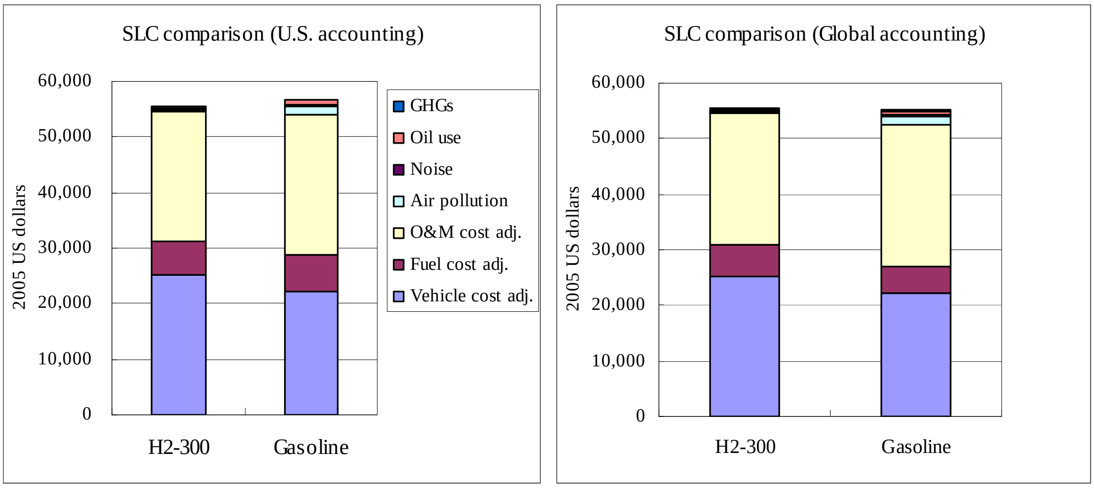


Figure 7-3 Societal lifetime cost comparison in 2025 adjusted with non-cost social transfers

7.2 Overview of buy-down cost methodology

The buy-down cost (BDC) of hydrogen FCVs is defined as the incremental expenditures on FCVs (the difference between the lifetime cost of the FCV and the lifetime cost of the gasoline ICEV) accumulated from the time of first market introduction of FCVs to the time at which the lifetime cost of the FCV (which will be declining over time due to leaning and mass production) equals the lifetime cost of the gasoline ICEV, as shown in equation 7-1. The date when the lifetime cost of the FCV equals the lifetime cost of the gasoline ICEV is designated the "breakeven" year t_e.

$$BDC = \sum_{i=t_0}^{t_e} [LC_i(FCVs) * Q_{fcv} - LC_i(GVs) * Q_{gv}] \qquad (7\text{-}1)$$

Where LC_i is the lifetime cost basis (consumer lifetime cost or societal lifetime cost) at year i, Q_{fcv} is the annual production volume of FCVs, and Q_{gv} is the annual volume of GVs replaced by FCVs. We analyze the buy-down cost for the US DOE Scenario 3 (Figure 4-10) with projections to 2050, as shown in Figure 7-4. Consumer/societal lifetime cost of a hydrogen FCV will be decreasing over time as we employ a learning curve model to estimate the fuel cell system cost. The vehicle cost and O&M cost of a conventional gasoline vehicle remain constant over time. Although gasoline fuel cost per mile declines slightly due to greater fuel economy increase relative to gasoline price increase, the consumer/societal lifetime cost of a gasoline vehicle will change very little. As hydrogen FCVs last longer than ICEVs, we can anticipate that Q_{gv} (number of GVs replaced by FCVs annually) will be more than Q_{fcv} (number of FCVs produced annually) when the benefit of the longer lifetime of FCVs takes effect in several years. At some time point, the total consumer/societal lifetime cost of FCVs will the same as that of GVs, and the cumulative cost difference is called the "buy-down cost".

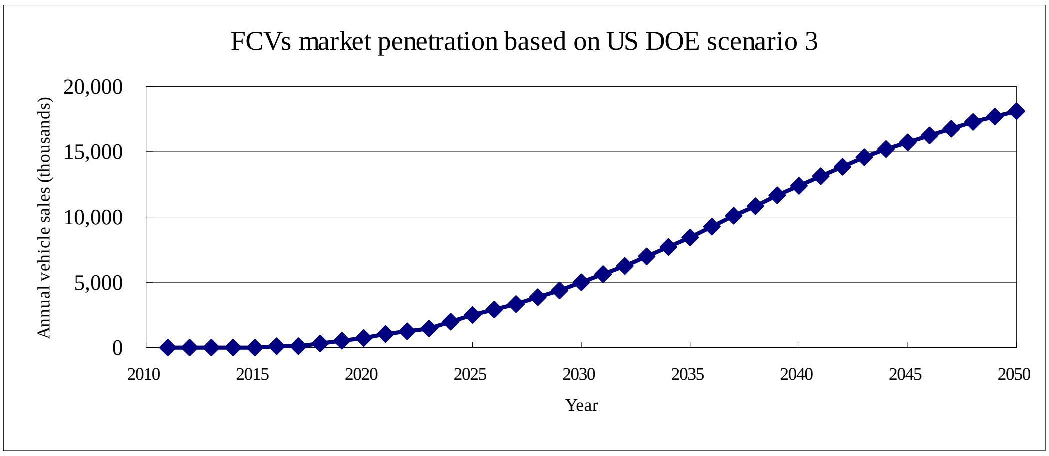


Figure 7-4 Hydrogen FCVs market penetration curve under US DOE Scenario 3

7.3 Buy-down cost results

We use two methods to calculate the buy-down cost of hydrogen FCVs: one is present value (PV) and the other is cash flow (CF). The PV method estimates the buy-down cost with two-step present value calculations. The first step is to estimate the total consumer/societal cost difference in each year of the simulation, where all the costs are expressed as the present value over specific vehicle lifetime and annual VMT in the year of the simulation. Note that this is different from the results shown in Figures 7-1 through 7-3, in which the present value comparison is based on the same annual VMT and the same vehicle lifetime as ICEVs because the cost-per-mile results have already accounted for the longer vehicle lifetime of FCVs and the comparison should hold the benefits (annual VMT and vehicle lifetime in miles) constant per vehicle. The second step is to take the present value of this series of annual cost differences from year t to the year zero (2012) when FCVs are introduced into market. Equation 7-2 shows the present value calculation, where PV_i refers to present value (year 2012) of total lifetime cost difference in year i, and LC_i is the lifetime cost (CLC or SLC) in present value[17] in year i.

$$BDC_{PV} = \sum_{i=t_0}^{t_e} PV_i\{[LC_i(FCVs)*Q_{fcv} - LC_i(GVs)*Q_{gv}]\} \qquad (7\text{-}2)$$

When LC refers to consumer lifetime cost (vehicle cost plus periodic costs), periodic costs include full fuel cost and O&M cost. This is termed the “CLC”. When LC refers

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[17] The present value here is calculated using specific vehicle lifetime, which is different from the results shown in Figures 6-1 through 6-3, because we should account for the longer lifetime of FCVs and a smaller number of FCVs replacing ICEVs at the fleet level for the buy-down cost calculation, where we hold fleet-level VMT benefits constant.

to societal lifetime cost, vehicle first cost excludes producer surplus on vehicles and periodic costs exclude taxes and fees and producer surplus on fuel but include external costs. This is termed the "SLC". Note that the calculation of the year-2012 present value involves two steps" taking the year-*t* present value of the lifetime cost stream of vehicles introduced in year *t*, and then converting year-*t* values to year-2012 present values.

The CF method is shown as equation 7-3, in which VC_i and PC_i refer to vehicle first cost and average annual periodic cost (fuel cost and O&M cost) respectively from the CLC perspective. On the basis of SLC, VC_i refers to vehicle first cost with producer surplus associated with vehicle purchase deducted, and PC_i to average annual periodic cost (fuel cost adjusted with producer surplus associated with fuel, O&M cost with taxes and fees deducted, and external cost). The "breakeven" year t_e is the year when the cumulative periodic cost savings cancel out the vehicle first cost difference. We estimate the societal lifetime buy-down cost from both the U.S. and global perspectives.

$$BDC_{CF} = \sum_{i=t_0}^{t_e} \{[VC_i(FCVs) * Q_{fcv} - VC_i(GVs) * Q_{gv}] + \sum_{i=t_0}^{t_e} [PC_i(FCVs) * Q_{fcv} - PC_i(GVs) * Q_{gv}]\} \quad (7\text{-}3)$$

Recall that we assume FCVs have a 10% longer lifetime than gasoline vehicles as electric motors last longer than engines[18]. To account for the different lifetime, we

[18] In theory this difference in potential lifetime might affect how much vehicles are driven each year. Likewise, in theory, differences in initial and operating costs between FCVs and gasoline ICEVs might affect how the vehicles are driven. However, we suspect that these effects would be small, mainly because consumers typically have limited alternatives to driving and limited flexibility in travel planning. We do not consider these effects here.

assume the number of displaced gasoline vehicles (Q_{gv}) is the same as that of produced FCVs (Q_{fcv}) for the first 10 years[19], and then after that the number of gasoline vehicles is 1.1 times the volume of FCVs, i.e. $Q_{gv}=1.1* Q_{fcv}$.

7.3.1 Present value method

Table 7-3 presents the calculated buy-down costs in constant 2005 US dollars with the PV method for the fastest market penetration scenario of FCVs, where low, medium and high refer to low, medium and high valuation of externalities. The “breakeven” will occur when FCVs achieve the same LC as conventional gasoline vehicles. For our reference case, hydrogen FCVs, on a CLC basis, would reach breakeven in 2022, and the buy-down cost would be nearly $30 billion. However, on a societal lifetime cost (SLC) basis with a US perspective, the buy-down cost of FCVs would be about $22 billion. At the time of SLC parity in the US, the hydrogen FCV penetration rate is about one million vehicles or 5% of the total US new vehicle sales. The SLC buy-down costs thus are significantly lower than the CLC buy-down costs. High valuation of external costs would reduce the buy-down cost by on the order of ten billion dollars. Under medium valuation of external costs, global accounting would have about $5 billion higher buy-down cost than the US accounting. Even under the low-external-cost case, FCVs would achieve SLC breakeven with gasoline vehicles before 2030 with the US accounting stance while global accounting would not within the time period studied (2010-2050) in terms of present values comparison.

[19] The benefit of the longer lifetime of FCVs won’t take effect until some gasoline vehicles begin to retire, which may take 5 to 10 years.

Table 7-3 Buy-down cost (PV) for the reference case (in 2005 US billion dollars)

Basis		Present value		
Consumer lifetime cost (CLC)	Buy-down cost	28.72		
	"Breakeven" year	2022		
Societal lifetime cost (SLC)		Present value		
		Low	Medium	High
US accounting	Buy-down cost	27.89	22.42	8.05
	"Breakeven" year	2022	2022	2020
Global accounting	Buy-down cost	-	27.89	9.68
	"Breakeven" year	>2050	2022	2020

Note: Low, medium and high refer to different valuation of externalities.

7.3.2 Cash flow method

Table 7-4 presents the calculated buy-down costs in constant 2005 US dollars with the CF method for the fastest market penetration scenario of FCVs, where low, medium and high refer to low, medium and high valuation of externalities. The "breakeven" will occur when the incremental vehicle first cost of FCVs compared to GVs equals the cost savings on periodic cost. For our reference case, hydrogen FCVs, on a CLC basis, would reach breakeven in 2028, and the buy-down cost would be about $40 billion. However, on a societal lifetime cost (SLC) basis with a US perspective, the breakeven year of FCVs under medium valuation of external costs would be two years sooner, and the buy-down cost of FCVs would decline by $7 billion to about $33 billion. At the time of SLC parity in the US, the hydrogen FCV penetration rate is 2.9 million vehicles or about 1% of the total US vehicle fleet. High valuation of external costs would reduce the buy-down cost by on the order of ten billion dollars. Under medium valuation of external costs, global accounting would have about $7 billion higher buy-down cost than the US accounting. Even under the low-external-cost case, FCVs would achieve SLC breakeven with gasoline vehicles before 2030 with the US accounting stance. With low valuation of externalities, hydrogen FCVs would also achieve cost competitiveness for the global accounting by 2031, but with about $12 billion more buy-down cost than that for the US accounting, which is different from the present value result.

Table 7-4 Buy-down cost (CF) for the reference case (in 2005 US billion dollars)

Basis		Cash flow		
Consumer lifetime cost (CLC)	Buy-down cost	40.48		
	“Breakeven” year	2028		
Societal lifetime cost (SLC)		Present value		
		Low	Medium	High
US accounting	Buy-down cost	40.42	33.48	22.79
	“Breakeven” year	2028	2026	2023
Global accounting	Buy-down cost	52.20	40.68	23.51
	“Breakeven” year	2031	2028	2024

Note: Low, medium and high refer to different valuation of externalities.

7.4 Sensitivity analysis

Tables 7-3 and 7-4 show that the buy-down cost of FCVs is significantly affected by the valuation of externalities: high-external-cost would cut the buy-down cost by $10-$18 billion relative to low-external-cost. However, these results are built on key assumptions on fuel cell performance and cost. The ultimate learned-out cost and performance of FCVs depend upon many factors, including technological advances, market penetration, infrastructure investment, and consumer acceptance. Besides these uncertainties, the future gasoline price is also an important determinant to the buy-down cost of hydrogen FCVs. Table 7-5 presents the sensitivity analysis using present value method when we use low-oil-price case and high-oil-price case from EIA AEO 2008. The projected oil prices per barrel for the period 2010-2030 are $52-$77 under the reference case, $32-$72 under the low-price case, and $80-$94 under the high-price case. The corresponding gasoline prices are $1.72-$2.42/gallon in the low-oil-price scenario, $2.16-$2.52/gallon in the reference-oil-price scenario, and $2.80-$3.47/gallon in the high-oil-price scenario. The results show that gasoline prices have significant impacts on the competitiveness of hydrogen FCVs. As shown in Figure 7-5 for the US accounting, the x-axis is the ratio of externalities or oil prices to the reference case, and the y-axis is the buy-down cost. The figure visually shows that both oil prices and externality valuations significantly affect the buy-down cost of hydrogen FCVs. In the reference-oil-price scenario, the difference of the buy-down costs for the US between low and high valuations of externality is about $20 billion. With medium external costs, the high-oil-price scenario, compared to the low-oil-price scenario, can have $16 billion savings on the buy-down cost for the US accounting. With the combination of low-oil-price and medium external costs or reference-oil-price and low external costs for the global accounting, hydrogen FCVs would not achieve cost competitive with gasoline vehicles with the PV method. From the global perspective, however, the high-oil-price scenario with medium external costs could reduce the buy-down cost by $8 billion, and the reference-oil-price with high external costs could cut the buy-down cost by $18 billion, relative to the reference-oil-price with medium external costs.

High oil prices would make FCVs more attractive to consumers beyond 2022 and the buy-down cost on a CLC basis is about $16 billion in terms of present value calculation. To put this in perspective, Delucchi and Murphy (2008a) estimate that the cost of defending Persian-Gulf oil used by motor vehicles in the US was between $6 billion and $25 billion in 2004. With medium external costs and the US perspective, the buy-down cost difference between the low-oil-price scenario and the high-oil-price scenario is about $16 billion, which is about one-fifth of 2008 capital expenditures for gasoline and diesel infrastructure ($87 billion as estimated by Thomas (2008)). With the high-oil-price scenario and the US perspective, the buy-down cost difference between low and high external costs is about $12 billion; with the global perspective, the difference is about $18 billion.

Table 7-5 Sensitivity Analysis of buy-down cost to changes in gasoline prices

EIA low oil price case

Basis		Present Value			Cash flow		
Consumer lifetime cost	Buy-down cost	-			58.58		
	“Breakeven” year	>2050			2033		
Societal lifecycle cost (SLCC)		Present value			Cash flow		
		Low	Medium	High	Low	Medium	High
US accounting	Buy-down cost	-	28.07	10.11	55.56	41.16	24.72
	“Breakeven” year	>2050	2022	2021	2032	2028	2024
Global accounting	Buy-down cost	-	-	11.56	82.28	50.75	25.64
	“Breakeven” year	>2050	>2050	2021	2038	2030	2024

EIA high oil price case

Basis		Present Value	Cash flow
Consumer	Buy-down cost	15.57	27.81

lifetime cost	“Breakeven” year	2022			2025		
Societal lifecycle cost (SLCC)		Present value			Cash flow		
		Low	Medium	High	Low	Medium	High
US accounting	Buy-down cost	17.05	12.10	5.16	28.18	26.43	21.34
	“Breakeven” year	2022	2021	2019	2025	2025	2022
Global accounting	Buy-down cost	24.70	19.67	6.36	35.55	30.59	22.30
	“Breakeven” year	2022	2022	2020	2027	2026	2025

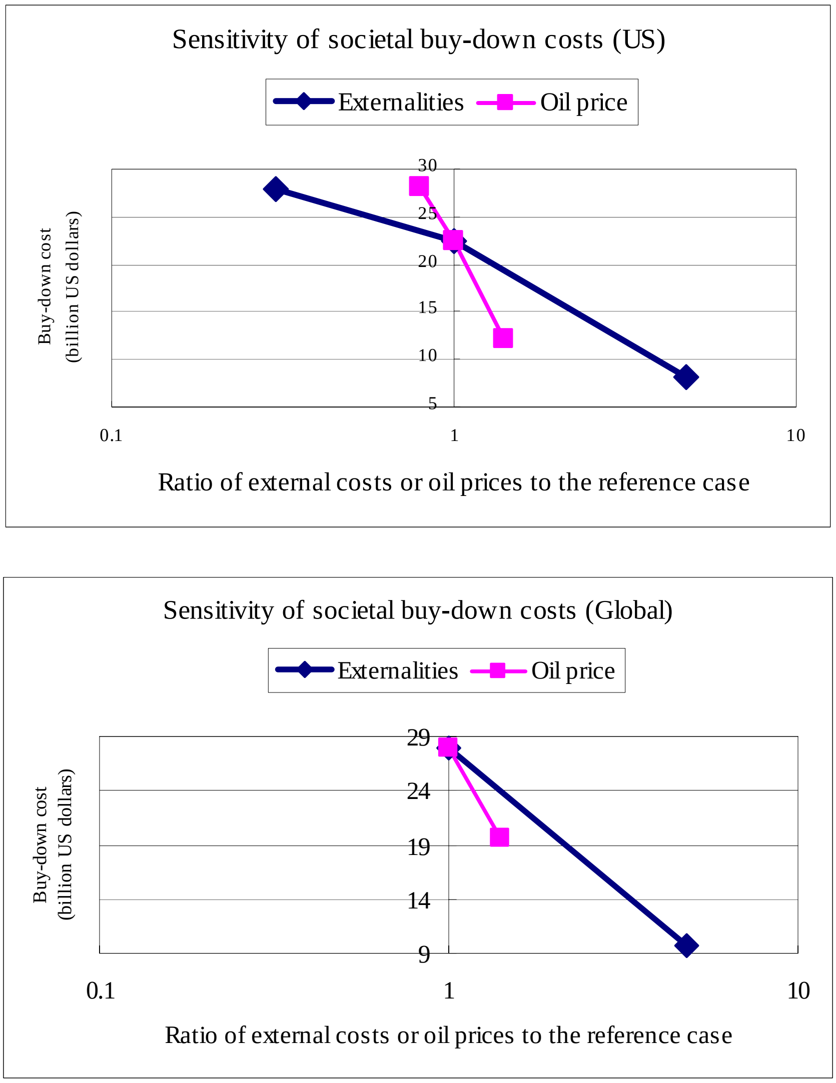

Figure 7-5 Sensitivity of buy-down costs (Present value results)

The buy-down costs with cash flow method are generally larger than those with present value method and the “breakeven” year is delayed for several years. With medium valuation of externalities, the societal buy-down cost difference between low-oil-price and high-oil-price cases is about $15 billion for the US accounting and $20 billion for the global accounting. Under the high-oil-price case, high-external-cost would save the societal buy-down cost by $7 billion for the US accounting, compared to low-external-cost.

Chapter 8 Conclusion

We have made a careful analysis of the full societal lifetime cost (SLC) of FCVs and gasoline vehicles, including consumer lifetime cost (CLC) (based in part on a learning-curve model for fuel cell system cost), external costs, and adjustments for non-cost social transfers. Our results show that FCVs would have higher initial vehicle cost even when mass produced. For our reference case, the magnitude of externalities for a hydrogen FCV can be \$700-\$900, about \$2,000 less compared to a gasoline vehicle. The external cost savings from FCVs with high valuation of externalities can be about \$7,000. On a CLC basis, the present value calculation shows that the buy-down cost of hydrogen FCVs for our reference case is about \$30 billion US dollars. When the medium-case value of externalities and non-cost social transfers are included, the buy-down cost from the US perspective is \$25 billion and the buy-down cost is \$28 billion from a global perspective with one year later the "breakeven" year than the US perspective. However, with the high-case value of externalities the societal buy-down cost is about \$14 billion lower compared to the medium-case value of externalities. This indicates that societal benefits of hydrogen and FCVs do make these vehicles more competitive than gasoline vehicles. With medium-value externalities, the buy-down cost from the US perspective would be increased under the low-oil-price scenario by \$4 billion and decreased under the high-oil-price scenario by \$11 billion, resulting in a spread in the buy-down cost of almost \$15 billion between the low-oil-price scenario and the high-oil-price scenario.

We conclude that the expenditures required to make hydrogen FCVs cost competitive with gasoline vehicles are quite sensitive to the valuation of externalities and to the future price of gasoline. Although the cash flow method presents higher buy-down costs, medium and high valuations of externalities for the US would reduce the buy-down cost by $7 and $18 billion when compared with consumer lifetime buy-down cost.

In response to the research questions we raised in Chapter 1, the conclusions are summarized as follows:

- In the early stage of hydrogen FCVs market introduction, a hydrogen fuel cell car may cost more than $100,000 to consumer. Even with mass production, the hydrogen fuel cell vehicle retail cost to consumer is still about $5,000-$6,000 higher than a conventional gasoline vehicle given the current and near-future technology and cost assumptions.
- Total annualized consumer lifetime cost of a hydrogen fuel cell car could be nearly $35,000 in 2012 and would decline to about $4,360 in 2025 with technology improvements and scale of economies. By comparison, our reference gasoline vehicle in 2025 would cost consumer about $4,370 annually, which is a little bit higher than the hydrogen fuel cell car though the gasoline vehicle cost is still lower than the fuel cell car.
- The total medium external costs over full fuel cycle and vehicle lifetime are about $800 for a hydrogen fuel cell car and about $2,800 for a gasoline car. High

valuation of externalities would increase the external cost to $5,700 for the hydrogen fuel cell car and $13,400 for the gasoline car. In 2012, the non-cost social transfers for a hydrogen fuel cell car are about three times that for a gasoline vehicle due to high vehicle cost of the fuel cell car and relatively high hydrogen fuel cost. However, when the fuel cell car achieves the “learned-out” cost in 2025, its non-cost social transfers would be about 78% of those for the gasoline car because of higher producer surplus associated with gasoline fuel.

- Societal benefits of hydrogen and FCVs would offset higher vehicle cost to some extent and make these advanced vehicles more competitive with conventional gasoline vehicles. High valuation of externalities would make FCVs more attractive to the society because these vehicles are superior over gasoline vehicles in terms of external costs associated with air pollution, oil use and GHGs (FCVs have much lower air pollution and GHGs over full fuel cycle and vehicle lifetime, and few externality with oil use).
- When we use medium and high valuations of externalities, these societal benefits of FCVs would cut the buy-down cost by $5-$18 billion and accelerate the hydrogen transition by a couple of years, depending on our stances (U.S. or global) and oil prices.
- The competitiveness of hydrogen FCVs is highly sensitive to both gasoline prices (highly positively correlated with oil prices) and valuation of externalities: high-oil-price case would save the consumer lifetime buy-down cost by about $13 billion compared to reference-oil-price case, and high-external-cost would reduce

the societal buy-down cost by $14 billion under the reference-oil-price case.

Our results are broadly consistent with the NRC study (2008), in which the buy-down cost (difference in vehicle capital cost and cumulative fuel cost) in the high-oil-price scenario is about $22 billion and the fuel-cost savings exceed the cost difference on vehicle purchase occur in 2023. The NRC study employs a cash flow method for the buy-down cost calculation, However, external costs and social transfers are not included. Including these, as we have done here, reduces the buy-down cost and results in an earlier breakeven year, and hence makes hydrogen FCVs more attractive to society. We estimate the buy-down cost with both present value method and cash flow method for both consumer lifetime cost and societal lifetime cost. For our reference-oil-price scenario, societal cost measure with medium and high external costs can reduce the buy-down cost of hydrogen FCVs by $5-$18 billion, and shortens the hydrogen transition timing by a couple of years for the U.S. accounting.

This study can provide an important reference for policy development for hydrogen FCVs by internalizing externalities. The external cost comparison between a hydrogen fuel cell vehicle and a conventional gasoline vehicle indicates that the societal benefits of hydrogen FCVs are not trivial. Externality tax on petroleum-based fuels or social friendly credit on hydrogen and FCVs could advance the research and development of fuel cell technology and hydrogen infrastructure, which to some extent would shift some market risk away from automakers in the early stage of FCVs market penetration. The buy-down cost results with sensitivity analysis present the magnitude of cumulative investment on hydrogen FCVs needed to achieve cost competitiveness. By comparison with expenditures on oil import and petroleum fuel infrastructure, the buy-down cost justifies the development of the advanced vehicles.

In this research, we consider hydrogen fuel cell vehicles only and compare with gasoline vehicles. However, future light-duty fuel cell vehicles are probably hybrids (fuel cell and battery). Also, some other advanced vehicle options provide societal benefits. Our future research will evaluate hybrid hydrogen fuel cell vehicles, electric vehicles, hybrid electric vehicles and hydrogen ICEVs from the societal lifetime cost perspective.

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