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The Plug-in Hybrid Electric Vehicle: Proliferation and Impact on Society and the Environment

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The Plug-in Hybrid Electric Vehicle:

Proliferation and Impact on Society and the Environment

An Interactive Qualifying Project Report

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Abstract

This report analyzes the impact of Plug-in Hybrid Electric Vehicles on the oil market and the environment and predicts the success of their implementation in Massachusetts. It describes the oil market and predicts that the introduction of PHEVs will result in savings of six million barrels of oil annually and a 10% reduction in oil prices after 50 years under ideal conditions. It also addresses the environmental concerns associated with the vehicles and predicts that PHEVs are indeed a green solution in Massachusetts, and will reduce carbon dioxide emissions by up to 22% after 50 years. System dynamics modeling is used to predict results for a number of scenarios, showing the impact on emissions, PHEV adoption, and average money saved. The scenarios include high oil prices, higher number of miles that a PHEV can run on electric, different charging times, higher battery capacities and different PHEV capital costs. It is also predicted that in Massachusetts, under ideal conditions, the gas car fleet will be completely replaced by PHEVs within 50 years.

The following document has been prepared in partial fulfillment of the requirements as a Bachelor of Science at Worcester Polytechnic Institute. The authors, Hunain Kapadia, Ishrak Khair, Tanvir Madan, and Andrew Teixeira, are submitting this document as an Interactive Qualifying Project for the above mentioned requirements. Hunain, Tanvir and Ishrak are Electrical and Computer Engineering students at WPI belonging to the class of 2010. Andrew is class of 2009, majoring in Chemical Engineering.

This project is an expansion upon the group's April report, Impact of Plug-in Hybrid Electric Vehicles on the Local Electric Grid, written in conjunction with Syed Kazim Naqvi and Timothy Yee. The group would also like to acknowledge the assistance given by Dr. John Bzura from National Grid and Professors Alex Emanuel and Khalid Saeed.

Executive Summary

The transportation and energy industries are two industries critical to society. Because of this, they are often at the heart of political, scientific and social debate. As gasoline prices rise and consciousness about its pollution increases, alternative solutions are sought out. New transportation technology is needed that is cost effective as well as environmentally friendly. This report analyzes the impact of Plug-in Hybrid Electric Vehicles on the oil market and the environment and predicts the success of their implementation in Massachusetts. To do this, the report was analyzed on two fronts: 1) the oil market, and 2) the environmental impact.

The oil market is key to determining the cost differential between PHEVs and gasoline vehicles. Currently, light duty vehicles have a 42% share in the total US oil consumption. The introduction of PHEVs in Massachusetts will be dependent on the cost of gasoline and the state of the oil market. This report first performs a detailed analysis into the domestic and foreign oil markets with respect to the PHEV market. It shows the sensitivity of the appeal for PHEVs as oil import costs increase, resulting in increasing gasoline costs and an increase in appeal for alternative fuel vehicles. It will predict the amounts of gas saved as well as oil price when the following parameters are varied:

- Maximum miles operating on electricity
- Oil price per barrel
- Average trip length
- Average miles per gallon

Sensitivity analysis shows that the introduction of PHEVs will help bring down the amount of oil required by the transportation industry. Within 50 years, the US will end up saving about 6 million barrels of oil annually. This decrease in demand will also lead to a 10% fall in oil prices. Table 0-1 summarizes how annual savings increase as oil prices per barrel increase.

Table 0-1 Annual $ saved as oil price per barrel rises

Initial Oil Price per bbl	Avg. $ saved per mile	Avg. Miles travelled in a year	$ saved per year
75	0.0852	12500	1065
100	0.1082	12500	1352.5
125	0.133	12500	1662.5

The authors also address environmental concerns associated with the adoption of these vehicles into society. Insight is given into the direct and indirect consequences associated with operating the vehicles. Specifically, this includes analyzing direct emissions from the vehicles as well as indirect emissions from the electricity generation power plants. Burning carbon fuels such as gasoline and other petroleum products produces the most harmful effects per unit of energy harnessed. Figure 0-1 shows the carbon dioxide produced per kilowatthour electricity generated.

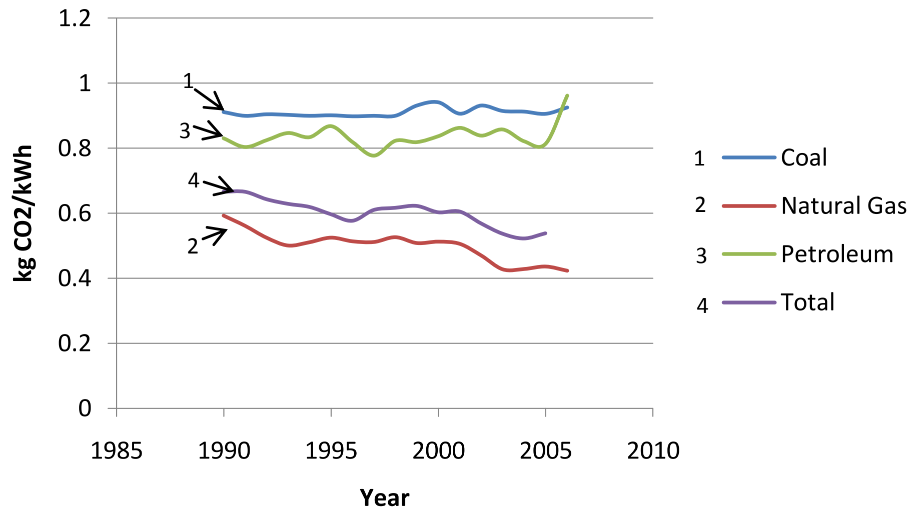

Figure 0-1 Carbon dioxide produced per kWh for various electricity generation methods in Massachusetts

Massachusetts generates most of its electricity from Nuclear (not depicted above, but 0 kg CO2/kWh) and Natural Gas. Coal, though a major polluter, is not as heavily used in Massachusetts. Petroleum is mainly used to meet peak demand so it is not a major factor in electricity generation for PHEVs due to its off-peak charging times. This project measured the CO_2 reduced by PHEVs when the following parameters are varied:

- PHEV battery technology
- PHEV engine technology
- Hybrid car useful life
- Hybrid Capital Cost
- CO_2 produced during different charging periods

Taking into account vehicle efficiencies and miles traveled per kilowatthour, this project has proven that electricity used to operate PHEVs result in 22% fewer carbon emissions than the use of gasoline directly in traditional vehicles after 50 years. When PHEVs are charged during off-peak hours (between 8 p.m. and 4 a.m.), electricity is being generated from nuclear, hydro electric and natural gas sources which produce low carbon emissions. PHEVs are only environmentally unfavorable under strained conditions where charging is done during peak hours of demand, particularly between 12 p.m. and 4 p.m., or when vehicles are continually operated for extended trip lengths. Table 0-2 depicts the impact on CO_2 reduced when vehicles are charged during the lowest demand period, between 12 a.m. and 4 a.m. when no other factor is varied.

Table 0-2 CO_2 Reduced when charged between 12-4am

Year	CO2 reduced as % of CO2 produced by all-gas car fleet
2008	0
2013	0.38
2018	1.17
2023	2.65
2028	4.90
2033	7.46
2038	10.04
2043	12.50
2048	14.75
2053	16.79
2058	18.60

If other technology factors increased, these percentages could increase greatly as well. These numbers show a significant improvement in CO_2 reduction and show the environmental benefits of PHEVs.

PHEV proliferation into Massachusetts was a key performance measure for this report. Under most conditions, PHEVs proved to be a highly favorable alternative to gasoline vehicles. Within 50 years, PHEVs were predicted to range between 85% and 100% of the market. Figure 0-2 shows how PHEVs will compose a major part of the automotive industry within the next 50 years.

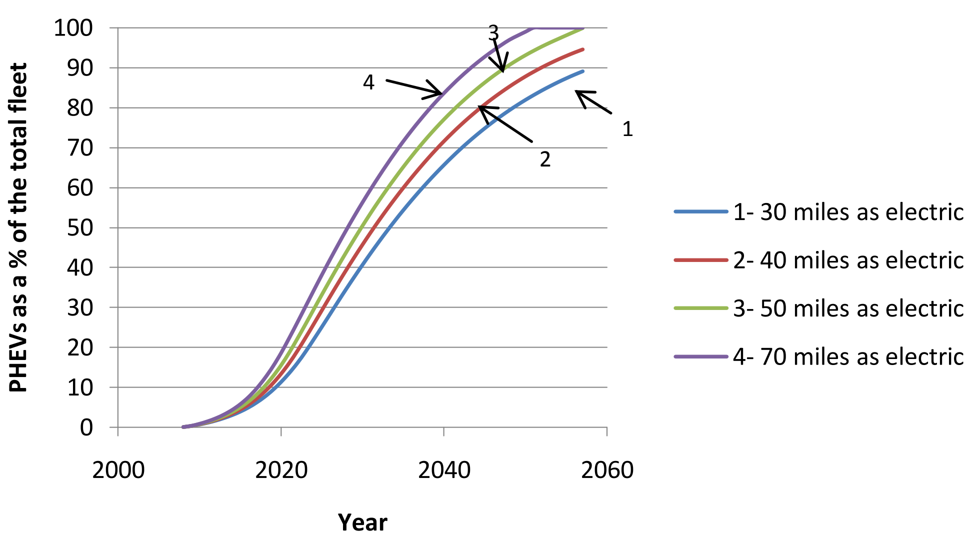

Figure 0-2: PHEV adoption in Massachusetts for various Maximum Miles on Electricity

This project ultimately assessed the impact of PHEVs on the state of Massachusetts. It shows that they will have positive impacts on the oil market, both decreasing demand and reliance on oil. It also results in a decrease in oil prices and increases transportation savings. The analysis also proved that the environmental results are favorable, and result in significant savings. Due to these effects, this project was able to predict that PHEVs are a viable solution to the transportation issues facing Massachusetts and are likely to replace pure gasoline vehicles within the next half century.

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1. Introduction

The future of the transportation industry has been in question since its earliest years. The notion of change was first brought about in the form of *feasibility* in the late 19th century. Once the concept of a car was deemed possible, the new problem of *reliability* needed to be addressed. Soon, as the automobile industry grew larger, *economics* became an issue. In the mid to late 20th century, having a vehicle simple wasn't enough. *Style* began to come into play as luxury models soon began to distinguish between the many models available to the consumer. Today, two unique and new driving forces are helping facilitate future innovation and change: efficiency and the environment.

In the first few years of the 21st century, Americans favored large vehicles which consumed what, at the time, was cheap gas in a strong economy. Hummers and pickup trucks were common and SUVs replaced sedans. This consumer trend soon changed. Today, as gas prices skyrocket, many consumers dread filling their tanks each week. The ability to drive further per gallon of gasoline is becoming more important to the everyday person as the realization settles in that oil resources are limited and prices will inevitably continue to climb.

The second major factor at play today is the social consciousness of the American people and government. It is well known that vehicle emissions are responsible for large amounts of greenhouse gas production and are leading contributors toward smog and general air pollution. Americans as a whole are starting to be more environmentally aware of these problems and are driving less, purchasing more fuel efficient vehicles, and driving more responsibly. In addition, the government is imposing stricter regulations on automobile manufacturers and offering incentives to consumers for investing in alternative fuel vehicles. These changes in societal trends will help drive the consumer transportation industry in a new direction.

Many solutions to these problems have been proposed. Alternative fuel vehicles have been conceived and prototypes have been created to run on electricity, solar panels, compressed air, biomass and even hydrogen. The most viable solution to this problem should already have been proven to be an efficient vehicle with respect to the aforementioned requirements. In addition it should also be able to merge into the current transportation infrastructure without requiring major investments. This discounts many of the solutions presented. Fuel Cell vehicles, which run on hydrogen, would need a major hydrogen infrastructure in place. Most practical forms of biomass and solar panels currently require more energy to produce than can be saved over the duration of the vehicles. Unfortunately, the technology simply isn't there to support these alternatively fueled vehicles.

One proposed vehicle seems to be a solution to these problems. Plug-in Hybrid Electric Vehicles (PHEVs), are automobiles which run on electricity for most of each trip but use gasoline as a supplement for longer trips. The concept is very similar to that of an electric car, however a gasoline electricity generator allows the vehicle to run for prolonged periods of time without a recharge. In addition, it maximizes the use of our current electricity and gasoline infrastructures. The future of PHEVs and their impact on the oil industry, the environment and on society as a whole will be analyzed throughout this report.

2. The Oil Market and PHEVs

2.1 Problem Definition and Background

Over the last few years, oil and gasoline prices have been in the mind of each and every American. With gas prices reaching extremely high levels over the summer and the resulting effect on the consumer's wallet, people have been searching for a solution to this crisis. This section will look into the background information associated with PHEVs and the oil industry.

This section will look into the oil consumption and production in the United States. The imports, exports, and the highly popular notion of 'oil dependency' will be analyzed with respect to the automobile sector and examined for their effects and importance.

2.2 Oil and America

In order to understand and appreciate the importance of the oil sector and its effect on the US economy and on society, a brief study on the availability of oil and its usage is necessary. It is important to start by examining world oil consumption before getting into specific details about the USA.

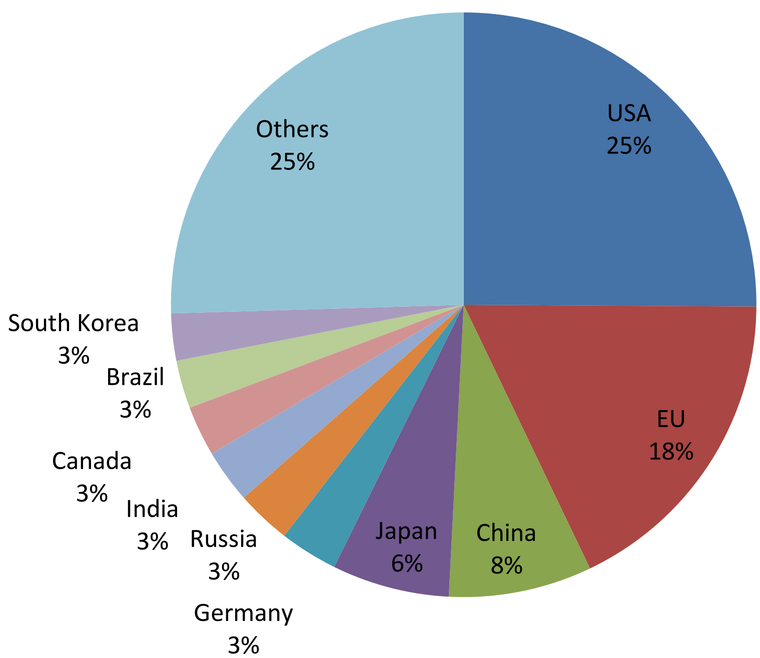

Figure 2-1 Oil consumption percentage by country[1]

Figure 2-1 shows a pie chart representing world oil consumption of the top 10 consuming countries. As it can be seen, USA consumes about 25% of the world's oil – this equates to an

[1] (NationMaster-Oil Consumption)

approximate use of about 21 million bbl/day[2]. One may not clearly understand how large this number is, but to put it in perspective one should think of world oil production. Saudi Arabia, the largest producer of oil in the world, produces about 9.5 million bbl/day [3] . Thus, the United States is actually consuming almost double of what is produced by the largest producer in the world.

2.2.1 US Oil Imports and Costs

In order to gain further knowledge, an analysis was performed to show the trend of US consumption over the years and the breakdown of this consumption into oil which is actually produced in the US and that which is imported. The United States spends enormous amount of money each year on oil imports and are constantly looking for ways to reduce this cost and dependence. Proposed solutions to an energy crisis have come to the forefront in recent years and have become crucial points of contention in the US today. Thus, it is important to provide information on US oil imports and on oil production in the US.

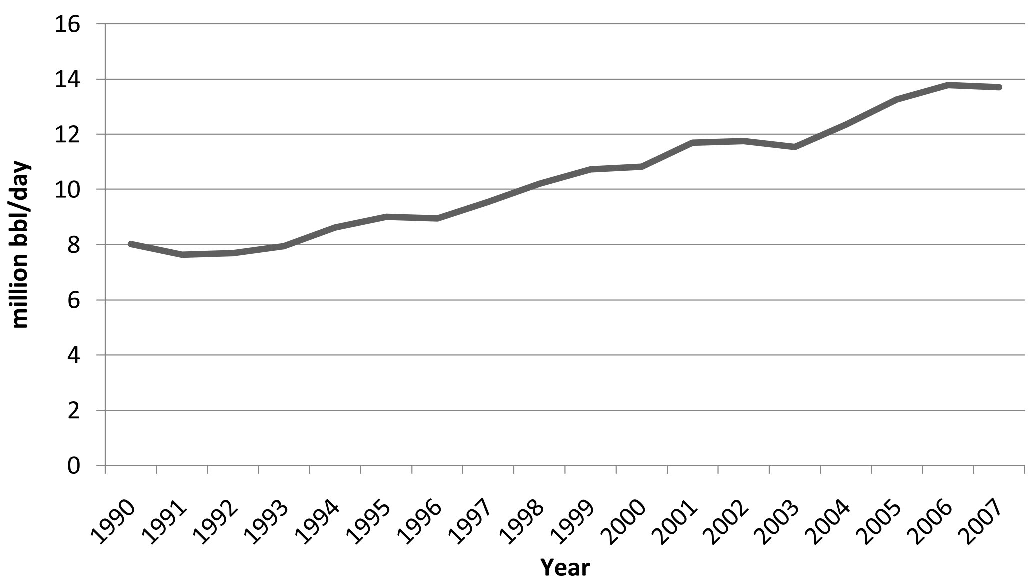

Figure 2-2 US Oil consumption over the years[4]

Figure 2-2 shows US Oil imports in million bbl/day for over the last 17 years. These numbers represent an enormous amount of American's money spent on oil imports. On average, the US spent $450 million for daily oil imports in 2004.[5]

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[2] (CIA - The World Factbook)
[3] (CIA - The World Factbook)
[4] (U.S. Imports of Crude Oil and Petroleum Products)
[5] (U.S. Imports of Crude Oil and Petroleum Products)

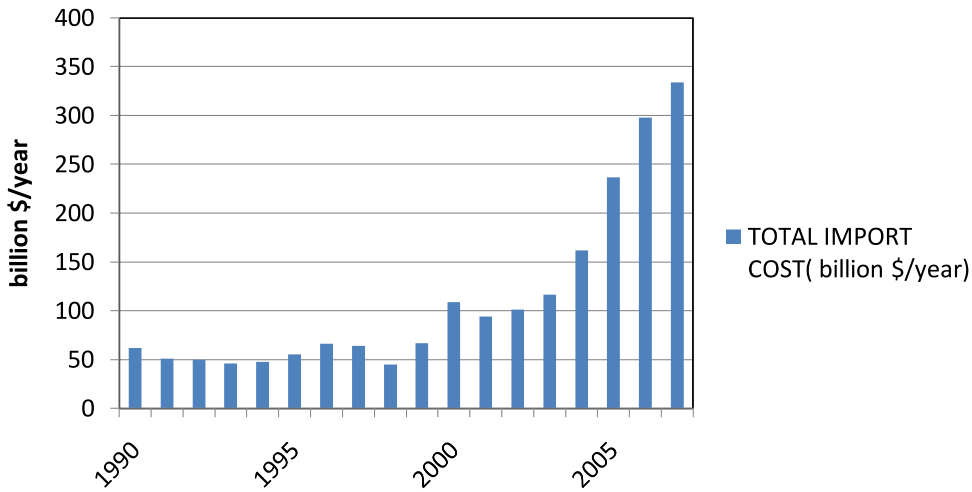

Figure 2-3 Total US Oil Import Costs since 1990

Figure 2-3 shows the billions of $/year spent on US oil imports. This cost has been rising consistently and is said to top $400 billion this year[6]. The proliferation of PHEVs could possibly reduce this cost and with less dependence on gasoline and will be analyzed in this project.

2.2.2 US Oil Production

A possible relief to the amount of money that the US spends on oil can be achieved through an increase of production at home. Nevertheless, it is estimated that even further domestic production of oil and off shore drilling will only reduce this dependence to a relatively small extent and will not be a permanent solution to the oil dependence problem.[7]

[6] (Reuters)
[7] (U.S. Imports of Crude Oil and Petroleum Products)

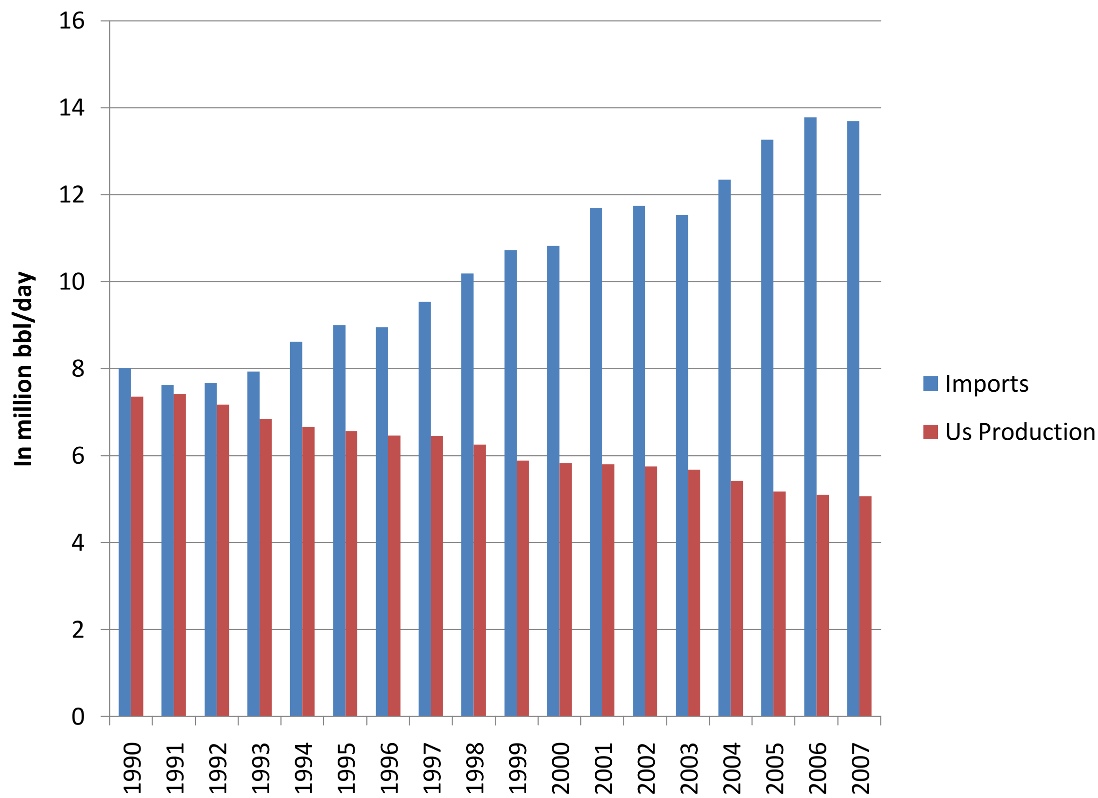

Figure 2-4 US Imports and Production over the last few years[8]

Figure 2-4 shows how US oil imports have been rising over the last few years at a rate of about 4.5% per year[9]. This further emphasizes how important it is that a solution is required which reduces the amount of oil that the US will consume and import.

This project will establish whether the proliferation of PHEVs can reduce the oil dependence of the United States and hence decrease the import requirement and costs associated with it. To do this, it is necessary to determine the proportion of oil that is used in the US automobile industry. This can then be separated into groups which are directly related to the project and analyzed for possible impacts.

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[8] (U.S. Imports of Crude Oil and Petroleum Products)
[9] (U.S. Imports of Crude Oil and Petroleum Products)

2.2.3 US Consumption by Sector

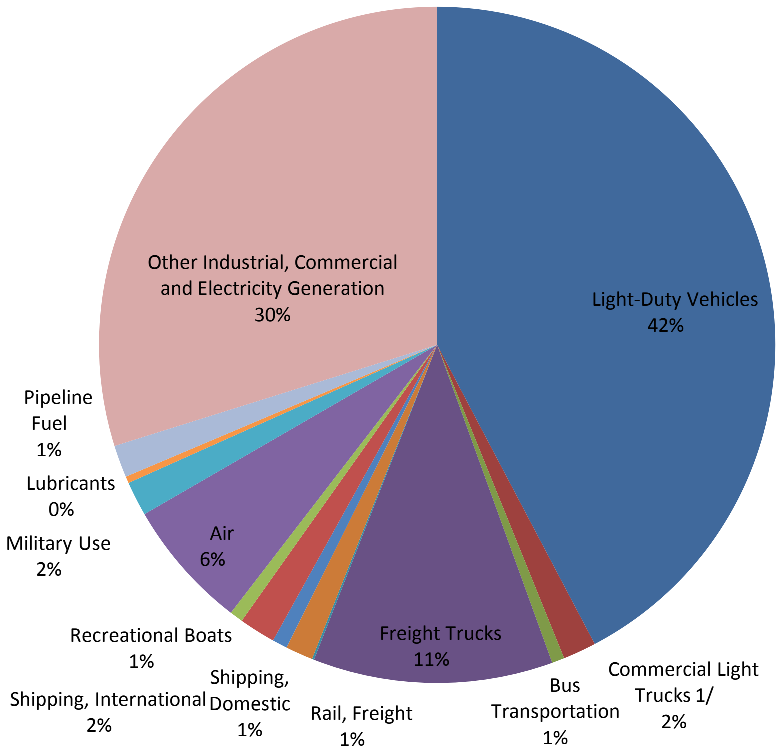

Figure 2-5 US Oil consumption by sector[10]

As it can be seen in Figure 2-5, Light Duty Vehicles consume 42% of US oil. Since such a large quantity of oil is being used by light duty vehicles, the penetration of PHEVs can potentially have a very profound impact.

By definition, light duty vehicles are defined as following[11]:

Light Duty Vehicles: Vehicles classed by Gross Vehicle Weight (GVW) as follows:

Class 1: 0 - 6,000 lbs. (passenger cars, minivan, utility van, multipurpose/sport utility vehicle, compact and full-size pickup)

Class 2: 6,001 - 10,000 lbs. (minivan, utility van, step van, crew cab pickup, full-size pickup, mini bus)

Class 3: 10,001 - 14,000 lbs. (mini-bus, walk-in, city delivery).

[10] (EIA)
[11] (Glossary of Terms: Tomorrow's Technician)

This class of vehicles is exactly where we can expect the onset of PHEVs and hence a possible reduction in oil demand as electricity begins to replace the gasoline requirement of the vehicles.

2.3 Change in behavior due to recent activity

Oil is known to be a extremely essential commodity with a very low price elasticity i.e. large changes in price bring about only small changes in consumption. The following research shows how rising oil prices have affected the volume of traffic on roads. Areas where alternative modes of travel besides cars are present and areas where alternative modes are not present both are compared. The research also points out how gas consumption of vehicles is effected by vehicle speed and how the sales of different categories of vehicles has been effected by rising oil prices.

Finally, shopping trends of hybrid vehicles have been examined and future predictions pertaining to growth of the hybrid car market have been discussed.

2.3.1 Driving patterns and distances

A rise in oil prices should cause a decrease in the volume of traffic on roads and highways. Table 2-2-1 shows the effect on the volume of traffic when gasoline prices rise by 20%.

Table 2-2-1 Increase in US oil price and its effect on traffic volume [12]

	Weekends	Weekdays
Average Effect, All Sampled Routes	0.12	-0.40
Statistical Significance	Not significant	1.4 percent*
No Rail Option	0	0
Statistical Significance	Not significant	Not significant
Parallel Rail	0.20	-0.69
Statistical Significance	Not significant	0.04 percent* *

The data was collected from 4 major counties of California over a period of 4 years. On average, over all locations, the price of gasoline in a given week had a negligible effect on the volume of weekend traffic, but on weekdays, higher gasoline prices had a small but statistically significant effect. A 20 percent increase in price, or 50 cents if the base price is $2.50 per gallon, would reduce weekday freeway traffic by an average of 0.4 percent. The effect would occur entirely in the response at rail-accessible freeway locations, as shown in the last two rows of the table. At those places, a 20 percent price increase would reduce weekday traffic by an average of 0.69 percent. That result is very significant, although it amounts only to about 730 fewer vehicles out of an average of more than 106,000 vehicles per weekday at those locations. Gasoline prices did not affect weekend traffic volume

[12] (Congressional Budget Office)

at any of the locations, nor did they affect weekday traffic counts where rail commuting was not an option.

Recent empirical research suggests that total driving, or vehicle miles traveled (VMT), is not currently very responsive to the price of gasoline. A 10 percent increase in gasoline prices is estimated to reduce VMT by as little as 0.2 percent to 0.3 percent in the short run and by 1.1 percent to 1.5 percent in the long term. Figure 2-2-6 shows that even though the price of gas has doubled from $1.50 to $3, the consumption of most types of gas continues to see an increase. The decrease in consumption in any grade of gas is hardly noticeable.

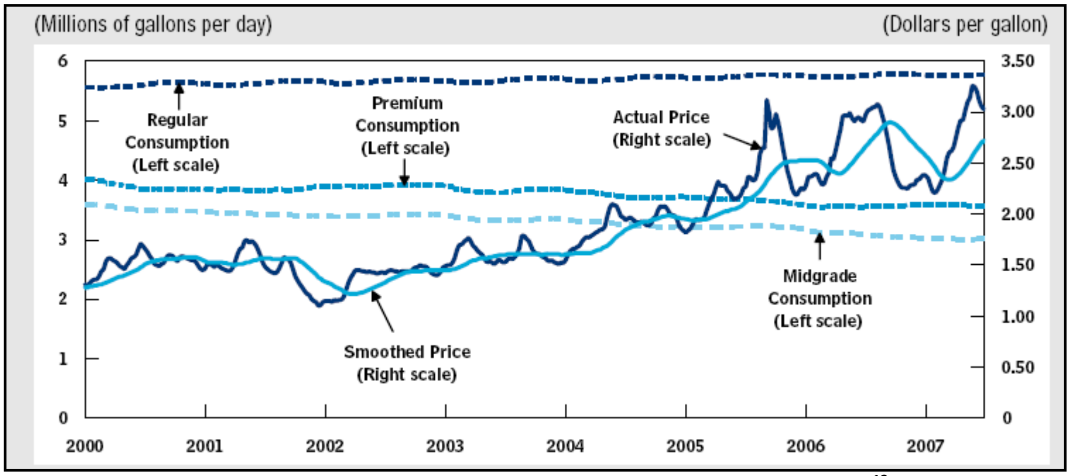

Figure 2-2-6 US retail prices and consumption of Gasoline in[13]

Another way that motorists can reduce their fuel costs is to drive more slowly. The incentive to slow down will depend on how much gasoline prices have increased, how much fuel would be saved by slowing down, and how much motorists value their time while driving. The value of the potential fuel savings from slowing down is rather small compared with reasonable measures of many motorists' value of time, so the likely effect of gasoline prices on highway speeds also should be rather small. For any given reduction in speed, however, the fuel savings are greater at faster speeds and for less-fuel efficient vehicles. Figure 2-2-7 shows how fuel consumption is affected by varying speeds.

[13] (Congressional Budget Office)

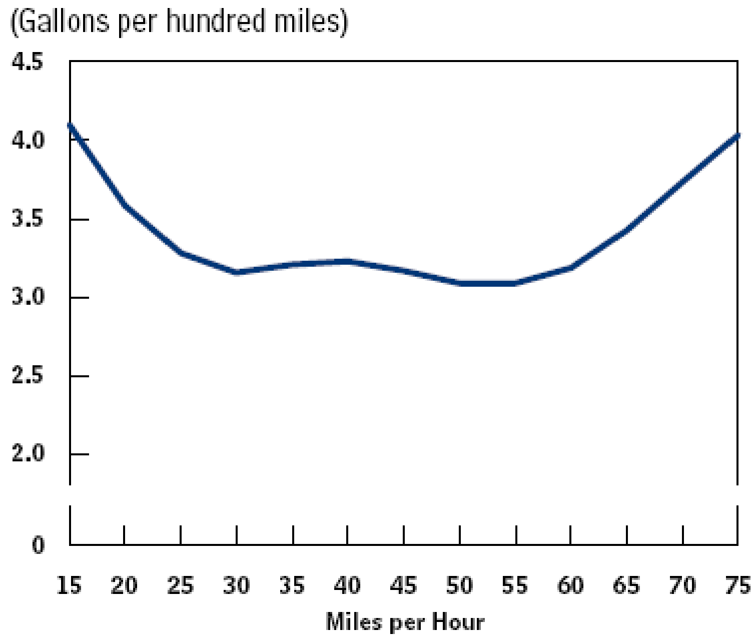

Figure 2-2-7 Average fuel Consumption and Vehicle speed[14]

It can be observed that for a particular range of vehicle speed, gas consumption is at its most efficient level. At slower speeds more gas is consumed and consumption increases at very high speeds too. Vehicles run most efficiently at speeds ranging from 30-55mph. By being more conscious of traveling speed, one can end up saving almost a gallon per hundred miles by driving at 60mph as opposed to 75mph.

2.3.2 Type of vehicles purchased

Rises in fuel prices have forced some people to change their automobile preferences in favor of smaller, more fuel efficient vehicles. Americans, especially, have been forced to give up their love of SUVs, one of the biggest form of gas guzzlers. Large manufacturing companies such as General Motors (GMC), who had a big share in the SUV market, have undergone sharp declines in sales and revenues and have been forced to restructure their companies. GMC is now investing millions in research and development of hybrids including PHEVs.

The research conducted analyzes the trends in the automobile market and statistics provide evidence of people’s willingness to give up gas guzzlers and switch to more efficient cars. Table 2-2 shows how market shares of different vehicles have varied over the years.

[14] (Congressional Budget Office)

Table 2-2 US market shares of different types of vehicles[15]

	2004	2005	2006	Change 2004 to 2006: Absolute (Percentage points)	Change 2004 to 2006: Percentage Change
Cars					
Subcompact and two-seater	1.3	1.3	1.4	0.1	3.8
Compact	19.2	19.8	19.4	0.2	0.8
Midsize	16.3	16.4	17.0	0.7	4.3
Large	8.0	8.5	9.4	1.4	14.4
Calendar Year Sales (Millions of vehicles)	7.6	7.8	7.5		
Change from Previous Year (Percent)	-1.2	2.2	-3.6		
Light Trucks					
Minivan	6.3	6.4	6.0	-0.3	-4.4
SUV	27.2	26.6	26.8	-0.4	-1.3
Pickup truck	18.4	18.6	17.8	-0.6	-3.3
Passenger or cargo van	3.3	2.3	2.2	-1.1	-32.0
Calendar Year Sales (Millions of vehicles)	9.4	9.1	8.4		
Change from Previous Year (Percent)	6.0	-3.3	-7.8		

Between 2004 and 2006, every major category of car gained market share and every category of light truck lost market share. The biggest gain was for large cars, which went from 8.0 percent to 9.4 percent of the market. The share of midsize cars also increased considerably, and although the market shares of compact and subcompact cars also increased, those gains were smaller. The underlying sales data indicate that those gains in market share for the most part reflect a decline in sales of light trucks, in every category, rather than an increase in car sales. Overall, the number of cars sold actually declined by about 1.5 percent each year from 2004 to 2006, or by a little more than 100,000 cars per year. Sales in the large-car category increased by 10 percent. Over that same period, however, sales of light trucks fell by 10 percent, with nearly 1 million fewer new vehicles sold per year.

Figure 2-2-8 shows the price's of different used vehicles as a function of time over the last 10 years.

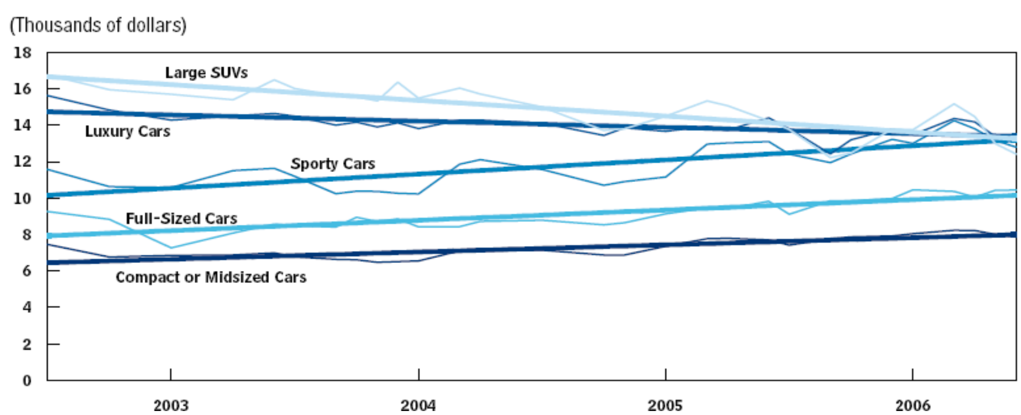

Figure 2-2-8 Average wholesale prices for used vehicles[16]

[15] (Congressional Budget Office)

The recently observed price shifts for new vehicles are reflected in used-vehicle prices as well. Average prices of fuel-efficient used vehicles have been rising, and those of less-efficient vehicles have been falling. In both markets, consumer preferences for fuel-efficient vehicles should be similarly affected by rising gasoline prices—which should affect prices similarly in both markets. Even if consumer preferences were not affected in exactly the same way by gasoline prices, price increases on fuel-efficient new vehicles would cause the prices on similar used vehicles to rise as some consumers shifted from buying new vehicles to buying similar used vehicles. Similarly, smaller price increases on less-fuel efficient new vehicles would limit how quickly prices could rise for comparable used vehicles. New-vehicle prices serve as a ceiling on consumer willingness to pay for used vehicles.

2.3.3 Possible added appeal for hybrid vehicles

The trend for rising sales in hybrids when gasoline prices spike is evident in Figure 2-2-9. It shows how the sales of 6 different hybrid cars rise and plummet from June 2005 to May 2006.

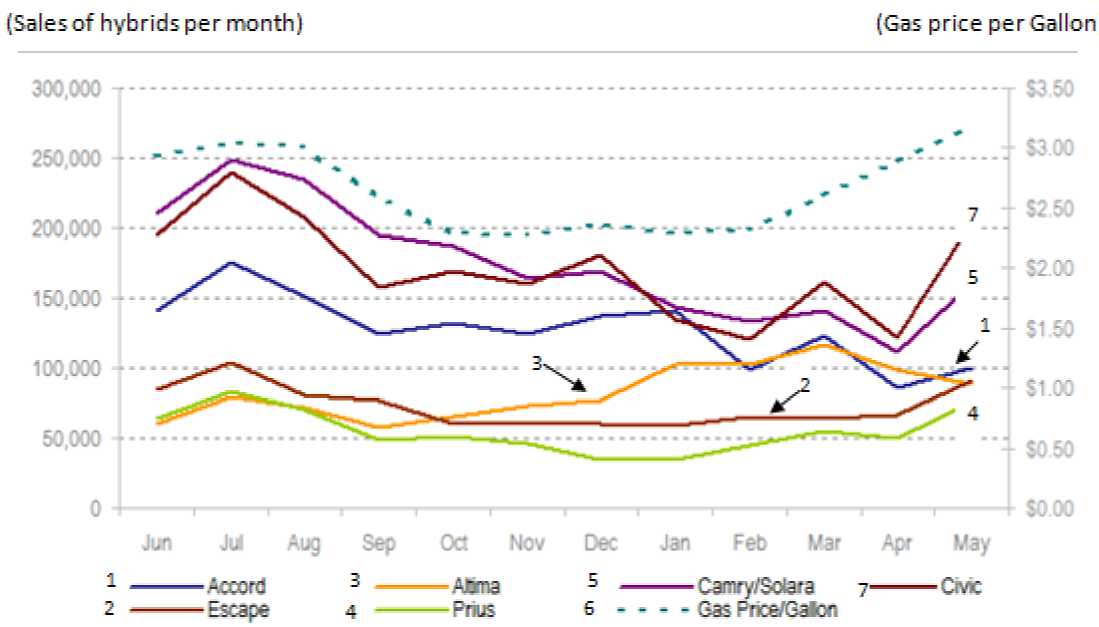

Figure 2-2-9 Hybrid shopping trends[17]

The trend of sales of hybrid vehicles follows the trend of gas prices. When gas prices slide, sales drop and when gas prices rise, sales increase. Sales of different models are shown out of which the Escape is an SUV and the Civic and Camry are sedans. It can be observed that the sedans are very popular as hybrids as compared to SUV's, which are less popular.

[16] (Congressional Budget Office)
[17] (Seeking Alpha)

Competition in the hybrid segment is projected to intensify further in the coming years. According to the report [18], there will be as many as 65 hybrid models—28 cars and 37 light trucks—in the market by 2010, with sales expected to reach nearly 775,000 units, or 4.6 percent of the total U.S. new light-vehicle market.

An estimated 187,000 hybrid vehicles were sold in the U.S. market through the first half of 2007, accounting for 2.3 percent of the total U.S. new light-vehicle market through June. While sales of hybrid vehicles are projected to decline slightly in the second half of the year, the market is still on track to sell 345,000 hybrids in 2007—a 35 percent increase from the 256,000 hybrids sold in 2006.

[18] (Associates)

3. Environmental Impact of PHEVs

Over the past decade, an enormous movement has emerged to protect the environment. Scientific studies have measured trends in factors including carbon dioxide, nitrogen oxides, ozone layer depletion, climate change, spent nuclear waste and global warming. This report will primarily concern itself with the environmental impact associated with the operation of a traditional internal combustion vehicle as well as the indirect emissions associated with the generation of electricity used to operate PHEVs.

3.1 Environmental Problems and Background

3.1.1 Greenhouse Gas Effect

For nearly fifty years, scientists have attempted to prove the phenomena of global warming. In this theory of global warming, it is proposed that the average temperature of the planet is gradually increasing from year to year which will in turn have drastic effects on the environment and society. This effect has become of great concern with respect to the melting of the polar ice caps. Should the climate change as predicted, the polar ice caps will melt causing the sea level to rise, permanently flooding coastal communities around the world. These results are observed by the National Aeronautics and Space Administration (NASA) which predicts a drastic increase in average sea level in the future. The results can be seen in Figure 3-1. These drastic climate shifts will also affect ecosystems in the oceans as well as on land.

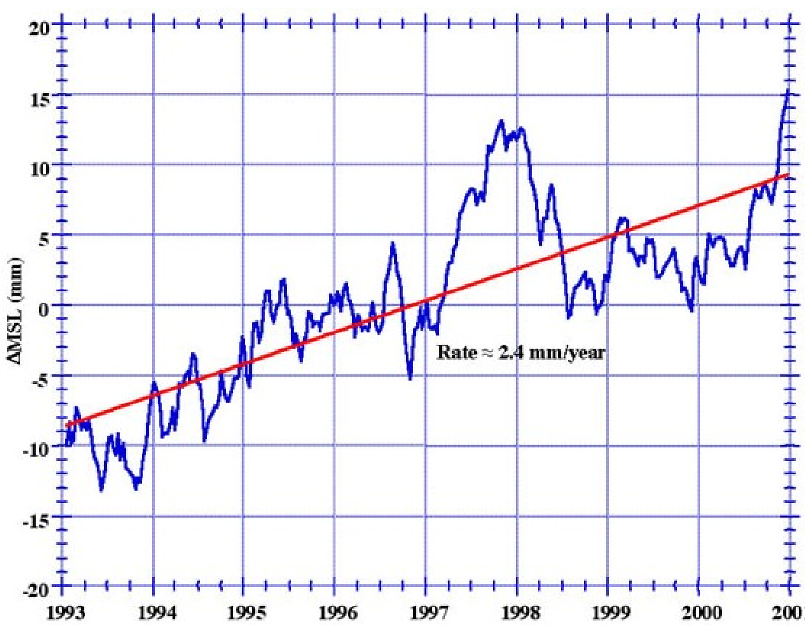

Figure 3-1 NASA study on depicting the increase in the global average mean sea level[19]

[19] (National Aeronautics Space Administration, 2001)

The most widely accepted explanation for these climate changes is the presence of greenhouse gasses. Greenhouse gases are chemicals which form an invisible layer of gas in the atmosphere. When sunlight passes through this layer, it forms a greenhouse effect where heat is kept in the lower atmosphere and not let out. Over the years, this effect will become significant when the gasses are not managed at the same rate in which they are emitted.

Greenhouse gasses include water (H_2O), carbon dioxide (CO_2), methane (CH_4), and Ozone (O_3). In all cases, it is necessary to have some of these gases to maintain the climate at the current temperature. Without them, the earth would be uninhabitable, but with too many it would be too hot to be inhabitable. For this reason, it is important to maintain the levels within a certain range.

Atmospheric water is a major factor in the weather systems experienced on earth and is considered to be a variable which should not be adjusted. Ozone, which is necessary to absorb sunlight in the upper layers of the atmosphere, is currently an area of concern for other reasons. The depletion of this layer exposes the lower levels of the atmosphere to the unfiltered sunlight, so ozone is considered a necessary greenhouse gas. Methane gas is an extremely strong greenhouse gas, but is relatively well contained and only emitted in small amounts. Should there be a large accumulation of methane in the future, it would be of more eminent concern. The final and most commonly known greenhouse gas, carbon dioxide, is of highest concern due to the enormous quantity of emissions and their immediate threat to our environment.

Carbon dioxide is emitted when carbon containing substances are broken down to create energy. Usually, plant life will convert this carbon dioxide back into oxygen, but in dense urban areas and when the overall output exceeds what plants can handle, it presents a problem. In the human body, food is broken down in a highly efficient process and carbon dioxide is emitted when the person exhales. In a gas car (1), home oil or natural gas (2) burners, and coal plants (3), some hydrocarbon is burned in the presence of oxygen to produce water and carbon dioxide.

$$C_8H_{14} + \frac{23}{2}O_2 \rightarrow 7H_2O + 8CO_2 \qquad (1)$$

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2 \qquad (2)$$

$$C + O_2 \rightarrow CO_2 \qquad (3)$$

This carbon dioxide emitted from combustion is considered to be the largest area of focus for ensuring that global warming does not cause serious damage. By creating processes which maximize the efficiencies of converting these energy sources to a useful means as well as minimizing the use of the low energy to carbon ratio, it is possible to greatly decrease carbon dioxide levels.

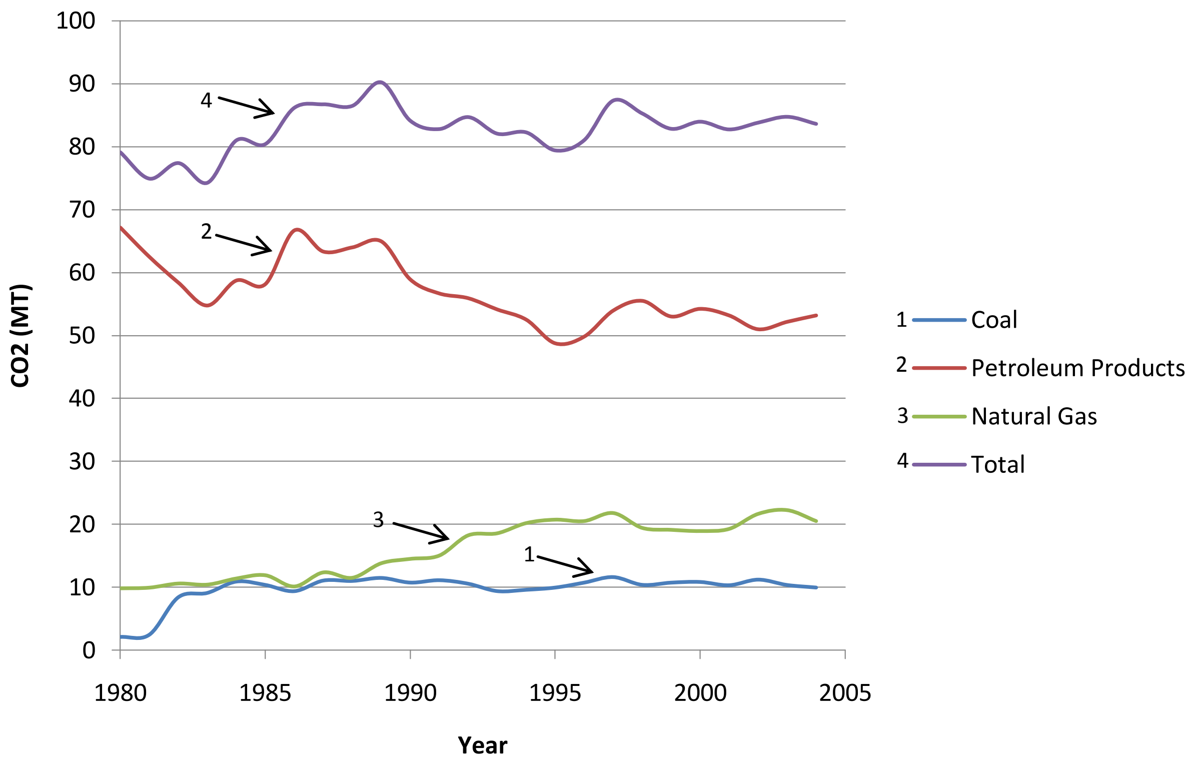

Figure 3-2 Annual carbon dioxide emissions by fuel type[20]

Figure 3-2 shows the trends of carbon dioxide emissions for the past twenty years. As is anticipated, the carbon dioxide emitted by petroleum used in electricity production is the only type that decreases. This is due to the decrease in petroleum burning in favor of more efficient fuels. Coal has a slight increase in carbon emissions due to a larger quantity of generation, though is mostly constant. The main increase is observed by natural gas which has become a chief contributor of additional electricity generation over recent years.

The government and people as a whole have recognized this threat and have taken a proactive approach toward fixing it. Emission laws have been put into effect for vehicles, manufacturing plants, and corporate electricity use. More recently, incentive programs have been put into effect which encourage consumers to waste less energy by purchasing low electricity appliances and hybrid vehicles. Even so, it simply is not enough. The problem will only be solved when new technology is adapted for all sectors of energy usage. In order to have a lower net carbon footprint people also need to be more aware of their effects on the environment and work to improve them.

[20] (Massachusetts Carbon Dioxide Emissions from Fossil Fuel Consumption (1980 to 2004))

3.1.2 Nitrogen Oxides

Nitrogen oxides, commonly referred to as NO_x gasses, are a chief contributor to acid rain and the phenomena in larger cities known as *smog*. Most commonly, these NO_x gases include nitric oxide (NO) and nitrogen dioxide(NO2).

The first phenomena seen is smog, which occurs when the nitrogen monoxide, for example, reacts with oxygen to form nitrogen dioxide. These gases are considered harmful in large quantities, especially on humid summer days.

$$2NO + O_2 \rightarrow 2NO_2$$

The second byproduct of these gases is seen with acid rain. Although not all NO_x gases react with water to form nitric or nitrous acid, a large enough amount does to react and has a negative effect on plant life and aquatic ecosystems.

$$NO_2 + H_2O \rightarrow HNO_2 + HNO_3$$

The emission of these harmful gases can usually be controlled by carefully managing the operating conditions during any type of combustion. On a small scale, where there is an oxygen rich, low temperature, lower pressure burn, the conditions are thermodynamically unfavorable to produce NO_x gases. During high temperatures, however, conditions are very conducive to their formation. In most vehicles, this is usually controlled through the use of a catalytic converter.

$$NO_x \rightarrow xO_2 + N_2$$

Even with these catalytic converters, the nitrogen oxides cannot be completely converted into safe byproducts. In older vehicles on the road, this process is also not as refined and cause the current fleet to be more inefficient.

3.1.3 Sulfur Dioxide

Many carbon containing substances also contain trace amounts of sulfur. When these compounds are combusted in the presence of oxygen, the sulfur often reacts in a side reaction to form sulfur dioxide.

$$S + O_2 \rightarrow SO_2$$

For the most part, this is not a major product. In the average, coal contains about 1% sulfur and between 70% and 90% carbon while petroleum can contain up to 6% sulfur and 83% to 87% carbon. If not contained properly, however, sulfur dioxide can be a chief contributor to acid rain. In industrial applications, regulations have been put into place to regulate these emissions. By reacting the flue gas to form a solid byproduct, the sulfur emitted to the atmosphere is minimal.

$$SO_2 + CaO \rightarrow CaSO_3$$

For vehicles running gasoline, sulfur dioxide is not a direct concern as most of the sulfur is removed prior to distribution to gas stations.

3.1.4 Nuclear Waste

Nuclear energy is considered to be one of the cleanest forms of electricity generation which can be applied on a large scale. It leaves virtually no carbon footprint and does not require the constant input of a petro fuel. It has also become much safer and the threat of a nuclear meltdown as decreased greatly with advances in technology. Unfortunately, however, there is a trade off. When uranium, or any other chemical, is reacted on a nuclear level, nuclear waste is produced. These byproducts of the fission reaction, usually referred to as spent nuclear waste or spent fuel, can remain radioactive on a dangerous level for thousands of years.

This waste is made up primarily of unreacted uranium and can, in theory, be reprocessed. In many parts of the world, this process is done to extract the uranium from the spent waste allowing it to be reacted again and making for less radioactive waste.

Currently, the United States does not have a permanent solution to nuclear waste. There are temporary storage facilities within many nuclear power plants which are capable of storing the waste for a relatively short amount of time. For the long term, however, there is no location large enough to hold the waste being produced. A plan to build an underground facility in Yucca Mountain, Nevada, is currently in the works.[21] Even so, the problem of transportation and sheer quantity remains an issue.

3.2 Social Awareness

During the age of the industrial revolution a century ago, little to no attention was paid to the environmental effects of highly pollutant factories. Automobiles did not have catalytic converters to remove nitrogen oxides from exhaust and dirty coal burring was a cheap and effective means for heating a home. Since this age in the late 18th and early 19th centuries, almost all innovation and environmental improvements have been driven by consumerism and not social conscienceless.

A major shift in society is taking place where a significant number of people are making the conscious effort to minimize their energy consumption. In some cases, this means purchasing *Energy Star* appliances or low energy lighting. In addition, some consumers are starting to be more conscious of their electricity usage so will turn off their lights when they are not used. Even so, these trends do, in the long run, offer a financial incentive as the consumer will save money on his electric bill.

In other cases, the driving force for becoming environmental conscience is purely due to a sense of societal responsibility. When people separate their paper, plastic, glass and cans in order to recycle them, there is no direct gain. The only rational behind doing this extra work is because it is the right

[21](Summerson, 2008)

thing to do. In addition, some consumers will opt to purchase electricity which is derived from renewable sources which adds an additional cost to their electric bill. These trends are purely motivated by social awareness, and feed directly back into the effect and willingness of people to invest in PHEVs.

3.3 Electricity Generation

Electricity is vital to sustain the standards of daily life in America. It is used in every part of society ranging from computers to cell phones and appliances. Unlike other resources, electricity is generated as it is not directly provided by nature. The energy from which this electricity is generated is of large concern and debate among scientist, politicians and private industry. As fuel sources become restricted and demand shifts, it is important to understand where the trends are headed. When looking at the energy division as a whole in Figure 3-3, a clear trend is seen where the transportation and commercial industries are increasing slightly while the industrial sector is demanding less energy, largely due to advancements in technology.

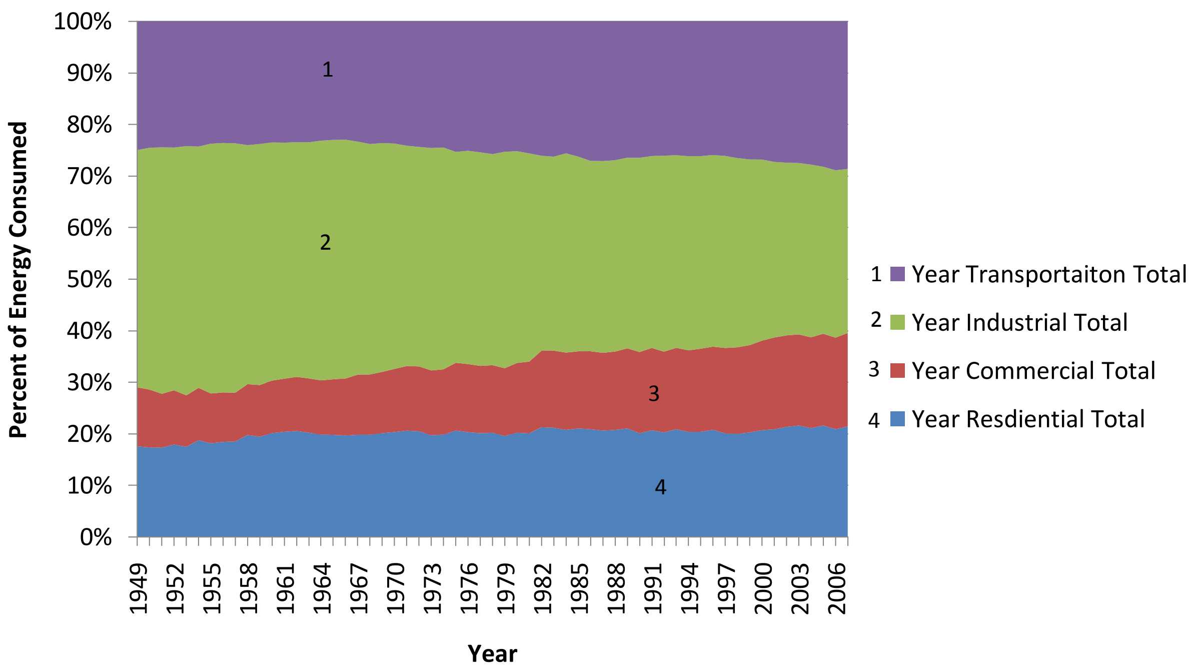

Figure 3-3 Energy consumption in Massachusetts by sector since 1949[22]

The term *energy* encompasses all forms of energy, namely mechanical, thermal, electrical, and chemical. Specifically looking at the electricity demanded over the past fifteen years, an increasing cyclical trend is observed as depicted by Figure 3-4. As the electronic age become more and more prevalent, Americans begin to consume more electricity each year. Though lights and appliances are becoming more efficient in general, new technologies are being implemented in each home that were not as common in years past, namely air conditioners. With the onset of these new domestic technologies, along with more industrialization and homes being built, the total electricity demand in

[22] (Net Generation by State by Type of Producer by Energy Source)

Massachusetts has seen a gradual increase and is expected to continue to increase in years to come, as seen in Figure 3-4.

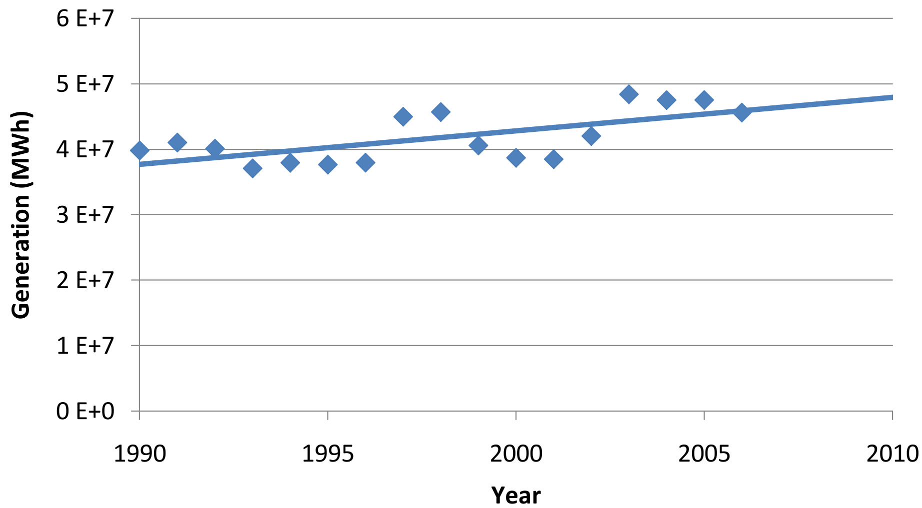

Figure 3-4 Electricity generation in Massachusetts shows an increasing trend[23]

With respect to the transportation sector, a comparison can be made between ordinary gasoline vehicles and the electricity used in PHEVs. When performing this analysis, however, it is important to analyze where exactly the electricity came from. This analysis on electricity generation will provide important comparisons to the environmental impact associated with the implementation of PHEVs.

In Massachusetts, electricity is generated primarily from natural gas, coal and nuclear power plants. This combination of generation sources is environmentally favorable as compared to other regions of the United States which rely more heavily on coal. Because of this, electricity in Massachusetts is often considered 'cleaner' than gasoline, thus contributing toward the appeal of PHEVs.

3.3.1 Coal

Coal is a natural resource made up primarily of pure carbon. It can be burned in the presence of oxygen in a combustion reaction to produce heat, which superheats water which drives steam turbines in power plants. Using coal as a means of electricity generation has been a cheap, relatively simple method for Americans to generate electricity for nearly two centuries. Until now, however, the environmental concerns brought about by the combustion process has not been addressed.

[23] (Net Generation by State by Type of Producer by Energy Source)

Today, coal is considered to be a major source of pollution in the energy sector. It is a chief contributor of carbon dioxide, which is now thought to be responsible for global warming.

$$C + O_2 \rightarrow CO_2$$

In addition, most coal plants are not efficient. Well over half of the energy content that each coal is capable of producing is lost to the environment in unconverted heat or frictional losses within the generators or turbines.

> *"CO_2 emissions from coal-fired electricity generation comprise nearly 80 percent of the total CO_2 emissions produced by the generation of electricity in the United States, while the share of electricity generation from coal was 51.0 percent in 1999. Coal has the highest carbon intensity among fossil fuels, resulting in coal-fired plants having the highest output rate of CO_2 per kilowatthour."*[24]

Numerous studies and research ventures have been conducted to improve the coal burning process by both making the current processes more efficient and reacting coal differently to extract the energy more carefully.

In addition to electricity generation, coal is also used as a heating source for steel production, cooking and a number of industrial processes. In the United States, it is looked at as both a problem and a solution. It is a problem for the environment, but a plausible solution to the energy crisis in the states because its abundance.

3.3.2 Natural Gas

Similar to coal, natural gas is also of concern for its greenhouse gas emissions. Not only does it produce carbon dioxide, but methane, its chief component. It is a dangerous greenhouse gas, far more harmful than carbon dioxide. Unlike coal, however, the energy is often extracted in a more controlled environment where the electricity produced per carbon is more manageable. Specifically, natural gas used to produce electricity in the United States is only 0.60 kg per kWh generated[25]. Because of this relatively low number, natural gas is preferable to coal and petroleum from the environmental standpoint.

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

On a domestic scale, natural gas can also be used for home heating and cooking. On an industrial scale it can be used for electricity generation, heating, and for production of important base chemicals such as hydrogen and ammonia.

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[24] (U.S. Department of Energy and the U.S. Environmental Protection Agency)
[25] (National Energy Information Center)

3.3.3 Nuclear

Nuclear energy has been the topic of numerous debates throughout the world, even sparking notions of war. The technology has the potential to cause great harm and threatens the safety of local residents. In addition, it produces highly hazardous, highly toxic waste that, if exposed, can have immediate consequences. This is unlike other fuels whose pollutants might have a greater effect on generations to come unless we do not change our habits. Thus, nuclear energy tends to have a more immediate impact on people today.

From a carbon standpoint, however, nuclear energy is a 'clean' solution to a major problem. By using uranium in a fusion of fission reaction, large amounts of energy are released by heat as the uranium is split into two lower molecular weight atoms. This energy is then harnessed by a standard heating process that vaporizes water which rotates a steam turbine and spins large electricity generators.

Since nuclear power makes up a large amount of the electricity generation in Massachusetts, it contributes significantly towards making electricity appear 'greener' than gasoline. Over the past few decades, nuclear energy has slowly become more popular and efficient. For the future, Massachusetts is considering numerous options for expanding its nuclear energy. This increase is likely due to the additional safety precautions and technology that are available in today's power plants. Reassurance has also come from gained knowledge and applications used in European countries such as France which has a high reliance on nuclear power for electricity generation.

3.3.4 Petroleum

Petro-fuels such as gasoline and diesel can be burned in the presence of oxygen to produce heat, carbon dioxide and water. With respect to electricity generation, this is the least desirable form. It is expensive, a large polluter of carbon products and relatively inefficient. On an industrial level, petroleum produces 1.969 pounds of carbon dioxide for every kilowatthour electricity generate.[26]

Unlike the other forms of generation, however, it has a relatively quick startup and shutdown time, so can be easily used to meet peak demand.

3.3.5 Hydroelectric

Ideally, electricity will be generated from renewable natural resources. Geothermal or hydro-electric energy is one means of harnessing such resources. This form of electricity generation takes advantage of forces applied by water. Geothermal is used when water beneath the surface builds up tremendous pressure which can spin turbines that generate electricity. Hydroelectric, similarly, converts gravitational forces on a body of water into electricity by spinning turbines on lower parts of a dam.

[26] (U.S. Department of Energy and the U.S. Environmental Protection Agency)

Both these methods are renewable due to the cyclical weather conditions on earth. After the water is passed to the lower reservoir, it is eventually used for another purpose and will evaporate under natural sunlight or other means. It will be replenished to the original, higher reservoir in the form of rain.

Environmentally speaking, hydroelectric generation is optimal. It produces little to no harmful emissions as it does not require any input of a fuel or chemical reaction. One harmful concern is the effect on local ecosystems. By introducing a dam system to a river or body of water, there is always a risk of disrupting the animal and plant life. Careful consideration has to be given to migration patterns, chemical levels and general consequences due to rerouting a water supply. Once implanted, however, no major additional harmful effects have been observed.

Unfortunately, hydropower cannot be introduced to any place where demand for electricity exists. Specific requirements have to be met before considering a location as a possible plant site. There has to be a large enough reservoir that feeds to a second reservoir significantly lower. Also, the water needs to have a means to be replenished without harming the ecosystem. In Massachusetts, there are few locations where this resource can be capitalized, and no locations where a single plant can become a key factor such as the Hoover Dam in Nevada-Arizona. There are also no thermal springs which can be used for electricity generation such as those used in Iceland.

The collective use of hydroelectric power in Massachusetts results in the annual generation of 1.5 million MWh per year, accounting for only about 3% of total electricity generation.[27] This number, though small, is not expected to increase dramatically due to a limited amount of natural resources.

3.3.6 Renewables

Renewable sources for electricity generation is a category that groups together any fuel or natural resources that does not become exhausted as it is consumed. Non-renewable resources such as natural gas, petroleum, and even nuclear consume some limited resources and will inevitably run out. It is important to conserve limited resources such as fossil fuel which is also needed for other processes such as synthesis of plastics. Because of this, fuel sources which neither consume nor alter the world's environment and resources are ideal forms of generating electricity.

In recent years, wind turbines have become more efficient, cheaper to construct and popular with society. Due to this shift, more wind turbines are being installed in residential as well as commercial areas. They are able to capture energy from passing wind and convert it into electricity inside a generator which can feed directly back into the grid. The only major form of pollution associated with wind is the visual pollution where some feel that their scenery is interrupted by the turbines. In Massachusetts, the numbers of turbines are increasing slightly each year, but will never be able to come close to completely meeting the electricity demand.

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[27] (Net Generation by State by Type of Producer by Energy Source)

Solar electricity is predicted to play a pivotal role in years to come. The potential of harvesting the sun's rays is great, though there is no technology-to-date that is capable of efficiently converting solar power into electricity. Solar panels with photovoltaic cells are only able to convert with about 30% efficiency. This number, though higher than years past, is nowhere near high enough to see much value over its short lifespan, especially when considering the enormous amount of energy needed to build the panels.

Biomass is a third large category for renewable fuels. The term biomass refers to any renewable organic material such as grass, wood and general crops which can ultimately converted into a usable fuel source. The chemical structure of many organic compounds, such as cellulose, shown in Figure 3-5, is not all that different from that of many of today's fuels such as gasoline, Figure 3-6. Under the right conditions, scientist have been able to decompose various forms of biomass so that it forms long, usable hydrocarbon chains such as octane, the chief component in gasoline. The use of cellulose is of particular interest due to its abundances in waste such as corn stalks, wood chips and grass clippings.

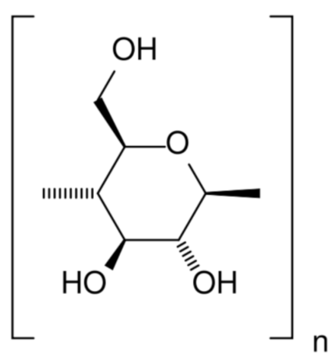

Figure 3-5 Part of long cellulose chains

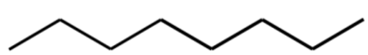

Figure 3-6 Octane, a chief component in gasoline

The main concern comes in the process of breaking down the biomass. The current processes are extremely labor intensive and often result in more energy put into the system than can be withdrawn from the products. Scientists are now researching new methods, such as the use of bacteria or molten salts, that promise to someday improve the method and allow for a new, renewable fuel source.

Today, all forms of renewable fuel only sum up to 6% of electricity generation in Massachusetts.[28] It is likely that this number will increase in the coming years as Americans demand cleaner fuel sources that decrease our dependency on foreign energy, increase the utilization of our local resources and helps protect the environment.

3.3.7 Comparison by Generation Type

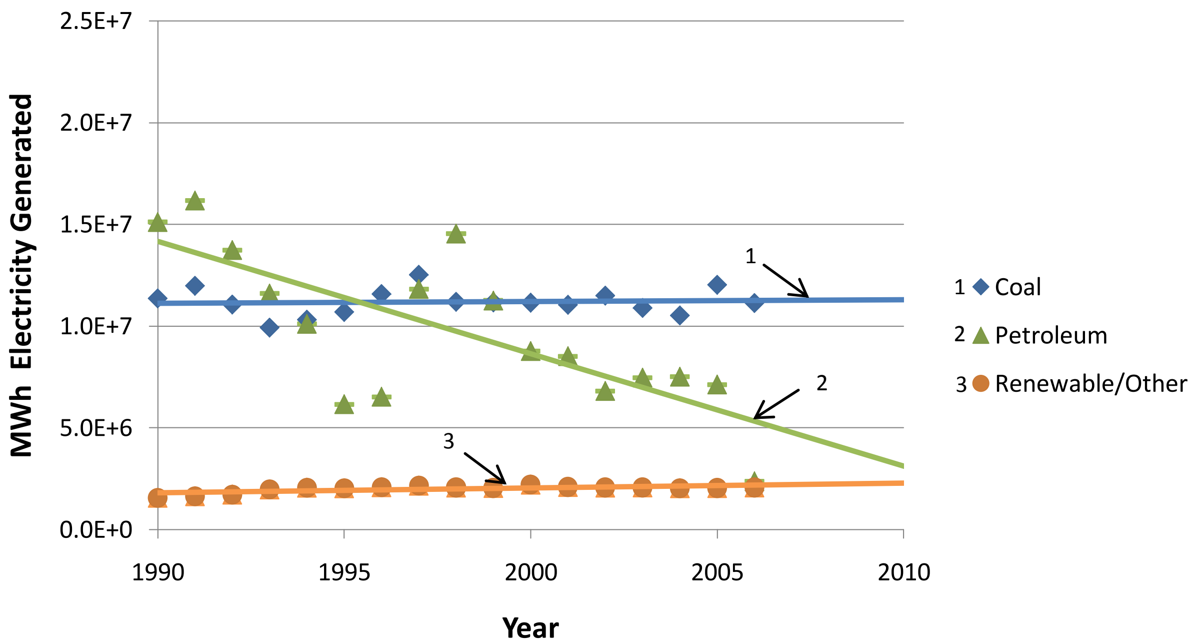

Figure 3-7 Annual Coal, Petroleum and Renewable electricity generation trends in Massachusetts[29]

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[28] (Net Generation by State by Type of Producer by Energy Source)
[29] (Net Generation by State by Type of Producer by Energy Source)

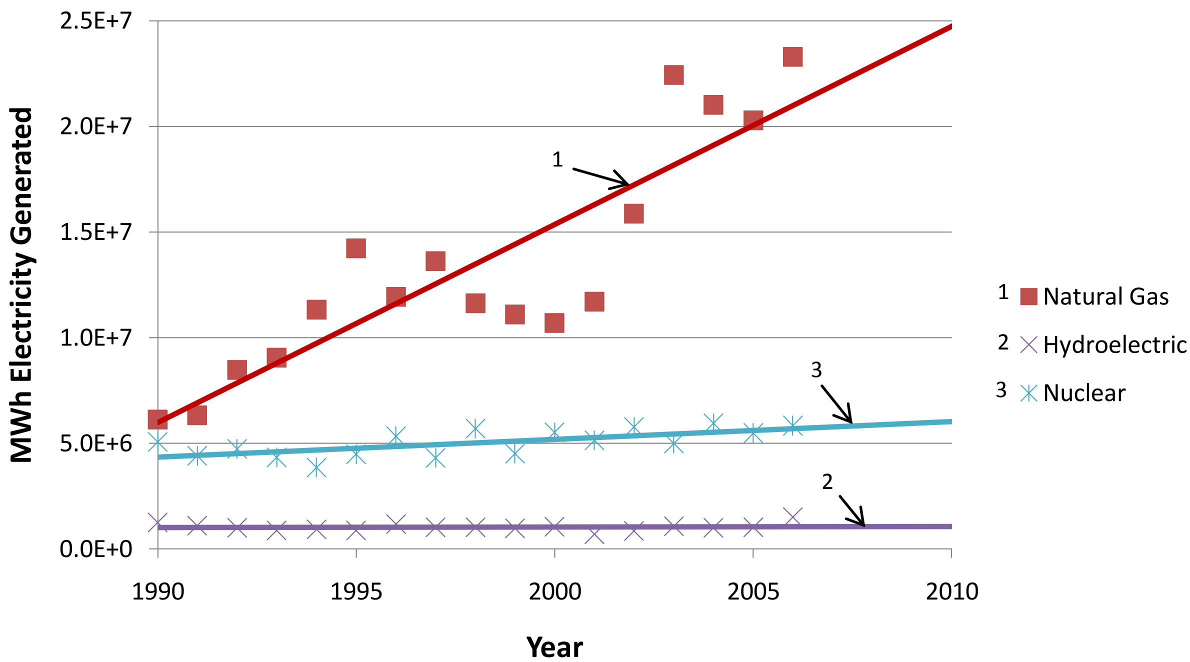

Figure 3-8 Annual Natural Gas, Hydroelectric and Nuclear electricity generation trends I Massachusetts[30]

In Figure 3-7 and Figure 3-8, net trends of all major electricity generation sources can be seen since 1990. Several sources, though increasing, have remained relatively constant and do not show any signs of increasing in the near future. These modes of generation include Hydroelectric, Nuclear and Renewable sources. In large, this stability comes from limited natural resources, technology and societal views.

The only fuel source with an explicit downward trend is petroleum. As a fuel for electricity generation, it is extremely undesirable for a number of reasons. It is relatively inefficient, highly polluting and requires a constant input of petroleum fuels. As other sources have become more efficient and cost effective, petroleum has been used less. It is still used to meet peak demand, but does not operate 24 hours a day.

Coal, despite its dirty burn, has produced a near constant amount of electricity over the past few decades. For the most, the coal burning power plants responsible for this trend have existed for years and have been upgraded and maintained, but few new coal plants have been built in Massachusetts. In the future, two possible outcomes will be observed in the coal industry. As plants age, they might phase out and a decrease in electricity from coal will be observed. Should technology improve, namely through gasification and or carbon dioxide containment, electricity generation from coal might increase. For Americans, this particular solution might be desirable due to the abundant amounts of coal available in the United States.

[30] (Net Generation by State by Type of Producer by Energy Source)

3.3.8 Emission Comparison by Generation Type

Although the overall trends for electricity generation is important, it is also important to analyze the environmental efficiencies of each generation type to produce electricity. In Figure 3-9, the efficiency of different sources for electricity generation is plotted as it has changed over the past years.

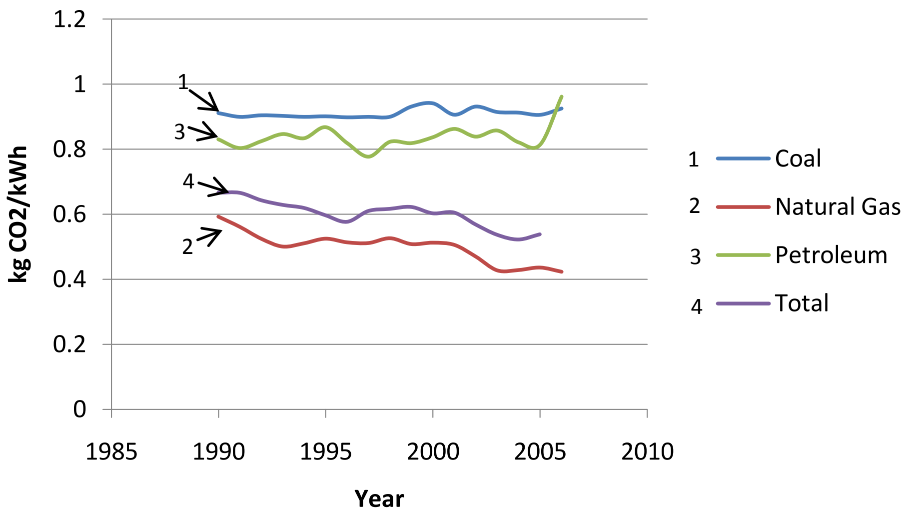

Figure 3-9 CO2 per kWh emission comparisons by fuel type in Massachusetts[31]

For every kWh of electricity generated, coal produces the most carbon dioxide. A close second is petroleum followed by natural gas. Not depicted here are hydroelectric, renewable energy sources, and nuclear as they do not contribute to the carbon emissions, but do lower the total CO_2 per kWh. It is also important to note that no major advancements have been introduced to improve the coal or petroleum burning processes, so the emissions remain relatively constant. Natural gas, however, has become more efficient over the past twenty years resulting in a more carbon efficient generation process. These statistics for Massachusetts are key in the analysis of PHEVs. These trends are responsible for making electricity a relatively 'green' form of energy.

3.3.9 Time of Day Emissions

Depending on the time of day that electricity is used, it may be generated from a number of different energy sources. For the most part, the method of production is governed by the nature of the technology, economics, and availability. This balance allows for certain charging periods to be ideal for generating electricity, while others may have highly negative impacts on the environment. Since it takes approximately four hours to fully charge the PHEV battery, the time of day in which the vehicles are charged becomes critical in the environmental analysis.

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[31] (Net Generation by State by Type of Producer by Energy Source)

By the nature of the technology, most of the generation types which run over night have less harmful emissions. Hydroelectric, Nuclear and a number of renewable sources such as wind operate for close to 24 hours per day due to their slow startup times, or the availability of the energy sources. Charging PHEVs in periods over night allows the vehicles to tap into this clean form of electricity, thus contributing toward the overall effectiveness of PHEVs to be categorized as a green alternative fuel vehicle.

Unfortunately, these clean forms of electricity generation are limited to a maximum hourly electricity, and cannot meet the peak demand required. For most of the day, this means relying on coal, petroleum and natural gas. Highly polluting coal has a slow start-up time and is often run for the bulk part of the day. Natural gas also runs for much of the day, but has more flexible operating conditions so it can be run more on-demand. It is also less polluting and a large reason why even during the daytime PHEVs charged in Massachusetts are more appealing than other regions. Petroleum burning plants only run to meet the peak demand during the afternoon hours. These charging periods will be tested further later in this report.

3.4 PHEVs vs. ICEs

On a technical scale, plug-in *hybrid* electric vehicles are conceptually more similar to the electric car than it is to the traditional internal combustion vehicles. The traditional car requires an internal combustion engine (ICE) to rotate a drive shaft which propels the car. Instead of an engine, PHEVs use four motors, one in each wheel, which relies on electricity to run the vehicle. In addition, the regenerative braking systems allow for electricity to be generated from the decrease in momentum as the brakes are applied, further increasing the efficiency of PHEVs, especially in city driving. The 'hybrid' aspect of the PHEV is essentially similar to a generator which produces electricity which can then power the vehicle. In both cases, the energy required to operate the vehicles either directly or indirectly produces harmful pollutants.

There are several scenarios in which PHEVs can be environmentally optimized. First, if charging is limited to overnight periods, it will ensure that PHEVs are always using the cleanest electricity available. In addition, if the average distance travelled by the vehicle is limited to 40 miles per charge, the gas combustion engine will not operate and will have no direct emissions.

Should the conditions be reversed, however, PHEVs have no advantage over traditional vehicles. If the charging period is during the peak of demand when the electricity relies heavily on carbon fuels, the emissions may cause a worse effect than had it operated strictly on gasoline. Also, when running for longer times without a recharge, PHEVs lose any edge on the traditional vehicles because both will be operating on gasoline. Currently, the efficiency of a PHEV running on gasoline is less than a traditional ICE vehicle.

In the future, the dynamics between these two types of vehicles may change drastically. These changes may occur with increased technology associated with electricity generation or better electric motors and batteries. On the other hand, with increased popularity, overnight charging has the capability of becoming equally as harmful as daytime charging. There are many factors involved with predicting the differences between PHEVs and traditional ICE vehicles, a number of which will be measured later in this report.

3.5 Government Policies

In any capitalistic society, it is easy for environmental aspects of daily life to be overlooked by large companies as well as consumers in favor of making a quick dollar. Government regulatory agencies, such as the EPA, have implemented a number of policies which ensure that the delicate environment is maintained in its current condition.

For electricity generation plants this means ensuring that the emissions are well controlled. Carbon fuels such as coal, natural gas and petroleum often contain sulfur compounds which can be neutralized into harmless byproducts with a little extra investment. Similarly, nuclear facilities produce spent nuclear waste which is undergoing strict transportation and storage regulations.

Government agencies also impose regulations on automotive companies. Gas guzzler taxes pose incentives for automobile manufacturers to design lighter more fuel efficient vehicles. In addition, tougher emission standards ensure that the vehicles are always as clean burning as possible with today's technology. In the future, the presence of more fuel efficient vehicles such as the common hybrid electric or less common plug-in hybrid electric vehicles may increase the efficiency of overall vehicle production fleets.

On the consumer scale, the government is involved mostly in the form of tax rebates and tax cuts. When the government recognizes a consumer investment into a technology that is more efficient than the norm, it can offer a tax incentive. Currently, these technologies include Energystar appliances, efficient lighting and hybrid vehicles. With the introduction of more PHEVs in the near future, appropriate tax incentives may arise based on the comparable efficiency of PHEVs with respect to the energy and the environment.

4. Method of approach

In an attempt to solve the problems presented in this report, System Dynamics modeling will be used as a method of approach. *System Dynamics* is a unique subject that uses computer based modeling to predict possible outcomes of a system. This form of modeling can be applied to many areas of interest, ranging from economics to business and health care. The model represents a problem that a system faces. At first, it is modeled to show how the system would normally behave. The model is then modified using policies that will hopefully help the system from either collapsing or failing. As with anything that can be modeled, however, there will never be a model that is completely correct—all models are somewhat wrong, because reality is unpredictable.

The first step to modeling is to determine a reference mode. The reference mode is based on historical data that shows how other systems' behave over time. The reference mode often reflects the problem as how the system will behave if left alone *then* the solution showing how the model should behave once new policies are implemented. The development of this reference mode has already been done in the previous report.

Once the reference mode has been completed, the next step is to build a *dynamic hypothesis*. The dynamic hypothesis shows the key factors to consider in the model, how each of the factors affect each other, the different flows between the factors and also the feedback loops within the system. A dynamic hypothesis is built showing the different connections between the factors. The factors are linked together with arrows and then positive and negative symbols showing the growth and decline that each factor has on the other. Using this overall diagram, the positive and negative feedback loops can be seen. Looking at all the factors, their connections and the feedback loops together, they serve as the basis for building the model.

Model construction takes into account all the factors mentioned in the dynamic hypothesis and several other minor factors. The factors are represented as *stocks* and the connections as *flows*. The stocks represent an amount of an item such as money, people, cars or any other measurable item. The flows represent the change in the stocks, both the inflow and the outflow. Examples of these flows might include birth rate, death rate, money saved or money spent. *Converters* are other major or minor factors that affect both stocks and flows. Combining all the stocks, flows and converters gives the basic concept of the model. They are then given numerical values and relating equations to make the system work. Once all the parts have been added, the model is tested. When done correctly, the first model will create similar to those predicted in the reference mode. This exposes the problem that the system faces and how the system is threatened.

Once the first simulation runs, the model represents the problem that the system faces. The next step is to implement different policies that will affect the model in such a way that it will stop the system from collapsing or failing. The policies that are implemented are designed to have the system to behave in a certain, preferred manner. They can be represented as government regulations or as some sort of industry standard that will affect the system. Once these policies are written, the model is run again to demonstrate how the system behaves with the new policy in place. This type of experiment is known as a *sensitivity analysis*. If the system responds well, then the policy that was implemented represents a possible solution. If the system does not respond well, then a new policy must me written and then retested. With multiple policies, the best one or combinations of the policies are implemented. These policies are put into effect and a game is created allowing users to change the parameters of the policy and seeing how the system behaves. However, as with all models, this too will simply be a simplification of a much larger complex real world situation and the project represents a simplified effort to understand it.

5. The effect on the Oil Market and Industry: Model Development

5.1 Dynamic Hypothesis

The dynamic hypothesis is a set of feedback loops that shows the overall behavior of the major variables in a system. For the model, the dynamic hypothesis outlines the various positive and negative feedback loops that influence the change in oil consumption brought about by an increase in plug-in hybrid cars on the road.

It is important to establish how this diagram should be interpreted. Each arrow begins from the *cause* element and ends at the element that is being affected. Whether the effect is a positive (increase) effect or a negative (decrease) effect is shown by the plus or minus operator next to the arrowhead.

When considering the effects of a change in one element on other elements or variables, it is assumed that all other elements do not change.

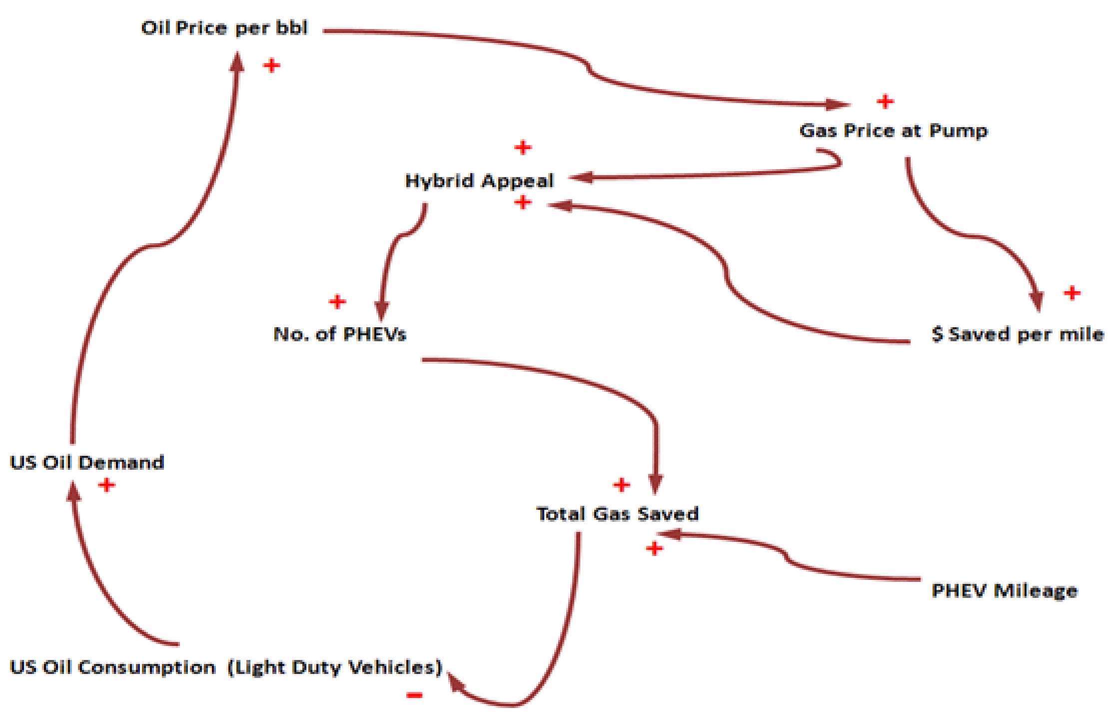

Figure 5-1 Dynamic Hypothesis of the Oil Sector

5.1.1 Explanation of Major feedback Loops

The major variable that drives the model is the Number of PHEVs. Therefore, the explanations of the feedback loops that follow will assume a change, particularly an increase, in the Number of PHEVs. This will allow for an understanding of whether the feedback loop is either positive or negative. If a change in Number of PHEVs causes a series of effects through a loop that finally causes the same change back to it, then it is a positive feedback loop. If the change causes an eventual opposite change back into the Number of PHEVs it is a negative feedback loop. This report will investigate each of the pathways starting from and leading back to the Number of PHEVs and classify them as either positive or negative feedback based on the abovementioned criterion.

Loop 1 : As the Number of PHEVs on the road increases, the Total Gas Saved increases since each PHEV consumes less gasoline than a regular gas car. When Total Gas Saved increases, the US Oil Consumption for Light Duty Vehicles (LDVs) decreases since lower gasoline consumption leads to lower oil consumption. Decrease in US Oil Consumption leads to lower US Oil Demand. Lower US Oil Demand leads to a decrease in the Oil price per Barrel, since the US has a very high share in World US Oil Consumption. A decrease in the Oil Price per Barrel leads to a decrease in the Gas Price at the Pump. The decrease in the Gas price at the Pump leads to lower Appeal for hybrids, which in turn decreases the Number of PHEVs on the road. Thus it is a negative feedback loop.

Other Loops :

An increase in the Gas price at pump leads to an increase in the $ saved per mile, which leads to an increase in Hybrid Appeal.

As PHEV mileage increases in the future, it will lead to an increase in the Total Gas Saved which will then follow the loops mentioned above.

5.2 Model: The Oil Market and Industry

The oil market sector of the model is an attempt to address the possible change in the oil industry with the advent of PHEVs. The sector takes the look at the change in demand of oil due to the replacement of gasoline cars with PHEVs and the subsequent reduction of gas use. To do the same, the amount of gas actually 'saved' by each PHEV and how this relates to barrel of oil is examined.

To model a sector involving something as complicated as the oil industry some simplifying assumptions have been made. This includes a simple negative relationship between oil price and production since it has been modeled as a cartel industry. Overall, the model aims to establish whether PHEVs can reduce oil demand by a significant amount and decrease US dependence on oil.

Figure 5-2 depicts the oil market sector and a list and explanation of all the variables used.

5.2.1 Model Structure : Visual Layout

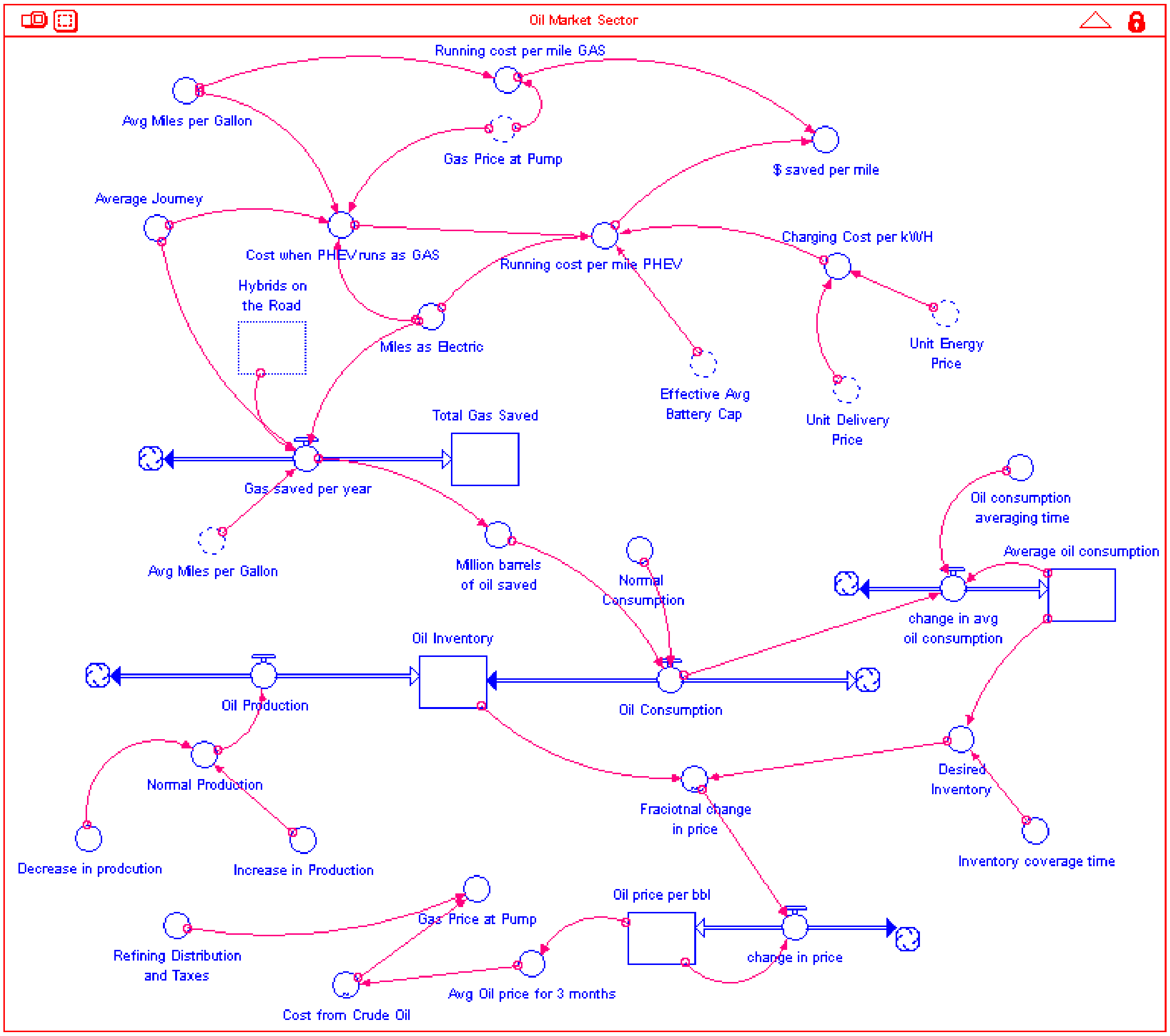

Figure 5-2 Oil Market Sector Model

5.2.2 Variable Definitions and Set up

1. ***Avg Miles per Gallon:*** Taken to be 25mpg. It is just an estimate to calculate gas usage of both regular cars and PHEVs incase the trip is longer than that which can be provided for by the battery.
2. ***Running cost per mile GAS:*** This is the cost per mile of a gasoline car in one year. It is determined by dividing the total miles in a yr by the average cost of gas.
3. ***Average Journey:*** Average distance travelled by a car in one trip.
4. ***Miles as Electric:*** The number of miles that a PHEV can run as a pure electric vehicle – it stems for the battery capacity and its associated technology.

5. ***Cost when PHEV runs as GAS:*** Cost when a PHEV operates on gas when it is used more than its purely electric capability. It is found by dividing these excess miles by the gas cost.
6. ***Charging cost per KWH:*** Cost associated with a charge of 1 kWh. It is the sum of the delivery cost and energy cost for 1 kWh.
7. ***Running cost per mile PHEV:*** Cost associated per mile for driving a PHEV. It stems from the charging cost of the battery per mile and the gas cost when the miles exceed the electric capability of the PHEV.
8. ***$ saved per mile:*** It is the amount saved in $ per mile while running a PHEV in comparison to a gasoline. It only incorporates the running cost and not any form of capital costs or maintenance costs.
9. ***Gas saved per year:*** The total number of gallons of gas saved per year by replacing regular gas cars with PHEVs.
10. ***Total Gas Saved:*** An accumulation of the 'gas saved per year' over the years.
11. ***Million barrels of oil saved:*** The barrels of oil saved in a year due to the advent of PHEVs. It is simply a factor of the total 'gas saved per year'.
12. ***Normal Consumption:*** The current normal consumption of oil in USA per year. It is expressed in billions of barrels of oil.
13. ***Fractional Change in Consumption:*** The fractional change expected in the oil consumption per year due to the dynamics of this model and the feedbacks associated with the oil sector.
14. ***Oil Consumption:*** The consumption of oil per year expressed in billions of barrels. It is determined by the normal consumption and the fractional change.
15. ***Change in avg oil consumption:*** The change in average oil consumption taking place over a period of 6 months.
16. ***Oil consumption averaging time:*** The time period over which an average for oil consumption is determined. It is taken to be 6 months.
17. ***Average oil consumption:*** The average oil consumption over a period of 6 months. It is used to determine the desired inventory as it is an accurate indication of the oil consumption.
18. ***Normal production:*** The current normal production of oil in USA per year. It is expressed in billions of barrels of oil. It is both the oil produced in USA and that imported to meet the demand.
19. ***Fractional Change in Production:*** The fractional change in production per year to compensate for the dynamics of the system. A cartel model has been used where the production increases as oil prices go down and vice versa.
20. ***Oil Production:*** The total production per year in millions of barrels. It is a combination of both the normal production and the fractional change.
21. ***Oil Inventory:*** The inventory of oil expected for a period of 6 months. It is the consumption minus the production and is measured in millions of barrels.
22. ***Desired Inventory:*** The inventory wanted for a period of 6 months. It is based on the average consumption.
23. ***Inventory coverage time:*** The time period for which inventory is expected to be present. This has been taken to be 6 months for the oil industry.

24. ***Fractional change in price:*** The fractional change in price determined by the dynamics of the model. To be specific, it depends on the desired inventory and the actual current inventory. A higher desired inventory in relation to the actual inventory will lower the price and vice versa.
25. ***Change in price:*** The fractional change multiplied by the current oil price per barrel.
26. ***Oil price per bbl:*** The international price for a barrel of oil. It has been initially taken to be $100. It changes depending on the inventory and consumption and directly affects the production.
27. ***Avg Oil price for 3 months:*** The oil price per barrel averaged over a 3 month period to form a required delay to determine gas prices.
28. ***Cost from Crude Oil:*** To determine gas prices we have concluded that there are 2 major factors – one relating to crude oil and the other to distribution and taxes. This variable looks at the crude oil factor and related the oil price per barrel to the cost of gasoline per gallon.
29. ***Refining Distribution and Taxes cost:*** The other contributing cost for finding the gas price per gallon.
30. ***Gas Price at Pump:*** The cost a consumer pays at the gas station for a gallon of gasoline. It is made up of the cost from crude oil and from refining, distribution and taxes.

5.2.3 Stock flow Structures

Stock-flow structures of Average_oil_consumption

1. Average_oil_consumption(t) = Average_oil_consumption(t - dt) + (change_in_avg__oil_consumption) * dt
2. INIT Average_oil_consumption = 24*365

INFLOWS:

3. change_in_avg__oil_consumption = (Oil_Consumption-Average_oil_consumption)/Oil_consumption__averaging_time

Stock-flow structures of Oil_Inventory

4. Oil_Inventory(t) = Oil_Inventory(t - dt) + (Oil_Production - Oil_Consumption) * dt
5. INIT Oil_Inventory = 24*365/2

INFLOWS:

6. Oil_Production = Normal_Production

OUTFLOWS:

7. Oil_Consumption = Normal__Consumption - Million_barrels__of_oil_saved

Stock-flow structures Oil_price_per_bbl

8. Oil_price_per_bbl(t) = Oil_price_per_bbl(t - dt) + (change_in_price) * dt

9. INIT Oil_price_per_bbl = 100

INFLOWS:

10. change_in_price = Oil_price_per_bbl*Fractional_change_in_price

Stock-flow structures Total_Gas_Saved

11. Total_Gas_Saved(t) = Total_Gas_Saved(t - dt) + (Gas_saved_per_year) * dt
12. INIT Total_Gas_Saved = 0

INFLOWS:

13. Gas_saved_per_year = IF (Miles_as_Electric<Average_Journey) THEN (Miles_as_Electric/Avg_Miles_per_Gallon*Hybrids_on_the_Road) ELSE ((Miles_as_Electric-Average_Journey)/Avg_Miles_per_Gallon*Hybrids_on_the_Road)

Although there are several stocks in this sector, some of them are actually those which have been defined in the previous model. In this description, the stocks defined in this sector will be explained and examined to gain a better understanding.

Average_oil_consumption: This stock represents the average oil consumption of the USA per year. The initial average oil consumption is taken to be 24x365 million bbl the US, as mentioned above in equation 2, consumes an average of 24 million bbl/day. There is only one inflow to this stock and it is the average change in oil consumption per six months. This is found by dividing the difference between the oil consumption and the average oil consumption by the averaging time of six months. This stock is useful in determining the desired inventory and hence the change in price by comparing the present inventory to the desired inventory.

Oil_Inventory: This stock represents the oil inventory in the United States over a period of one year. The initial value of this stock is also taken to be 24x365 million bbl. The inflow into this stock is the oil production which is taken as a constant to also be 24x365 million bbl/year. The outflow of this stock is the oil consumption. The oil consumption depends on the normal consumption of 24x365 million bbl/year and also the decrease in consumption brought about by the advent of PHEVs. This inventory is then compared to the desired inventory to find the fractional change in price per barrel of oil.

Oil_price_per_bbl: This stock represents the oil price per barrel. The stock has an initial value of $100 per barrel and it is experimented on by varying this price. There is only one inflow to this stock: the change in oil price. This change, as mentioned in equation 10, depends on the desired inventory and the oil inventory. Also, this stock influences the price of gas which has an impact on hybrid appeal and is the means of feedback to the rest of the model.

Total_Gas_Saved: This stock is a cumulative representation of the total gas that will be saved by PHEVs. The initial value is taken as zero since it is assumed that no PHEVs are on the road initially. There is only one inflow to this stock: gas saved per year. The gas saved per year comes directly from the number of PHEVs on the road and the number of miles that a PHEV runs as an electric vehicle. This directly replaces gas miles and hence leads to gas saved.

5.2.4 Parameters in model

14. $_saved_per_mile = Running_cost_per_mile_GAS-Running_cost_per_mile_PHEV
15. Average_Journey = 40
16. Avg_Miles_per_Gallon = 25
17. Avg_Oil_price_for_3_months = SMTH1(Oil_price_per_bbl,0.25,100)
18. Charging_Cost_per_kWH = Unit_Delivery_Price+Unit_Energy_Price
19. Cost_when_PHEV_runs_as_GAS = IF(Average_Journey-Miles_as_Electric)>0 THEN ((Average_Journey-Miles_as_Electric)*Gas_Price_at_Pump/Avg_Miles_per_Gallon)/Average_Journey ELSE 0
20. Decrease_in_prodcution = -24*365*time*0.001
21. Desired__Inventory = Average_oil_consumption*Inventory_coverage_time
22. Gas_Price_at_Pump = Refining_Distribution_and_Taxes+Cost_from_Crude_Oil
23. Increase_in_Production = 24*365*time*0.001
24. Inventory_coverage_time = 0.5
25. Miles_as_Electric = 30
26. Million_barrels__of_oil_saved = (Gas_saved_per_year*0.0322580645*28/42/1000000)*50
27. Normal__Consumption = 24*365
28. Normal_Production = 24*365 + 0*Decrease_in_prodcution + 0*Increase_in_Production
29. Oil_consumption__averaging_time = 0.5
30. Refining_Distribution_and_Taxes = 1
31. Running_cost_per_mile_GAS = Gas_Price_at_Pump/Avg_Miles_per_Gallon
32. Running_cost_per_mile_PHEV = Cost_when_PHEV_runs_as_GAS + (Charging_Cost_per_kWH*Effective_Avg_Battery_Cap)/Miles_as_Electric
33. Cost_from_Crude_Oil = GRAPH(Avg_Oil_price_for_3_months)
    (60.0, 1.52), (68.0, 1.69), (76.0, 1.92), (84.0, 2.10), (92.0, 2.33), (100, 2.49), (108, 2.68), (116, 2.91), (124, 3.11), (132, 3.32), (140, 3.49)
34. Fraciotnal_change_in_price = GRAPH(Oil_Inventory/Desired__Inventory)
    (0.00, 0.184), (0.2, 0.134), (0.4, 0.096), (0.6, 0.062), (0.8, 0.026), (1.00, 0.00), (1.20, -0.04), (1.40, -0.076), (1.60, -0.096), (1.80, -0.104), (2.00, -0.104)

6. Environmental effects of PHEV proliferation: Model Development

6.1 Dynamic Hypothesis

The first stage in model development was to establish a dynamic hypothesis. This dynamic hypothesis, as mentioned in 5.1, will describe the causal relationships between different elements in our model.

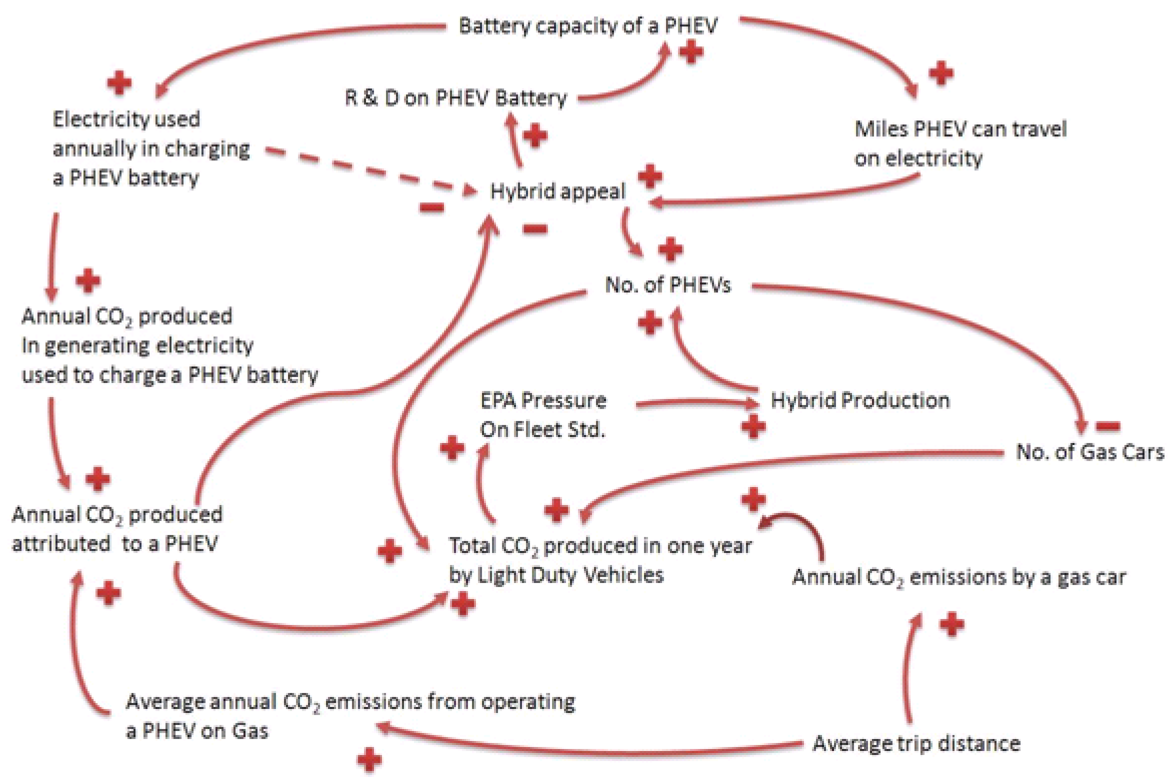

Figure 6-1 Dynamic Hypothesis of the Environmental Sector

6.1.1 Explanation of Major feedback loops

Loop 1: As the battery capacity increases, the annual electricity used in charging a single PHEV will increase. This is because more electricity is needed per charging session to fully charge the PHEV's battery. This means an increase in the amount of CO_2 that is produced annually as a result of generating this electricity for each PHEV. As a result, the annual CO_2 produced that is attributed to PHEV use increases. As more CO_2 is attributed to a PHEV, Hybrid Appeal decreases since environmentalists and other concerned parties, such as the government, will not favor increased CO_2 generation. This in turn will have a negative effect on research and development of PHEV batteries. Finally, a reduction in standard PHEV battery capacity will occur, which will use less electricity and generate less CO_2. Therefore, this loop can be classified as a negative feedback loop.

Loop 2: An increase in battery capacity will lead to an increase in PHEV electricity mileage. This is because the PHEV can run longer on electric mode before switching to gas mode. This will attract more people towards PHEVs and so Hybrid Appeal will increase. An increase in Hybrid Appeal will lead to more research and development of batteries, which will finally lead to an increase in battery capacity. Since battery capacity is reinforced through these causal relationships, this is a positive feedback loop.

Loop 3: As the number of PHEVs increase, the total CO_2 produced annually by light duty vehicles will increase. This is because there are more cars emitting and generating CO_2 from electricity generation. The Environmental Protection Agency will then raise the standard that light duty vehicles have to meet in terms of emissions. Since PHEVs have less emissions on average than gas cars, Hybrid Production will be favored and the number of PHEVs on the road will thus increase. Therefore, this can be rationalized as a positive feedback loop.

Loop 4: As the number of PHEVs increase, they will replace gas cars on the road and gas car numbers will decrease. Since gas cars have higher CO_2 emissions than CO_2 generated and attributed to PHEVs, the total CO_2 produced annually by light duty vehicles will decrease. This will mean a lower EPA pressure on light duty vehicle standards. One of the major ways CO_2 emissions will be reduced is through PHEVs, and when the EPA pressure is not very high, the need for PHEVs is not that great. Thus, hybrid production will decrease and the number of Hybrids will decrease. This is thus a negative feedback loop.

6.2 Model: The Environmental Sector

The environmental sector of the model is designed to be a measure of performance. It can also be modified slightly to affect Hybrid Appeal as well. Since CO_2 is shown to have an effect on Hybrid Appeal in our Dynamic Hypothesis, the sector has calculations that change Hybrid Appeal depending on how CO_2 emissions change due to gas cars and PHEVs. However, due to time constraints imposed on this project and the lack of EPA and government regulation data on fleet standards, an accurate means of representing how PHEV numbers change due to regulatory bodies responding to changes in CO_2 levels could not be established. This may be investigated in future works with this Project. Nevertheless, performance measures are employed in the form of stocks, flows and parameters that reveal how amounts of CO_2 are produced and saved in relation to variations in Gas car and PHEV numbers. Almost all the elements in our Dynamic Hypothesis will be incorporated into this sector in the form of variables. EPA standards, however, are not incorporated in the model since, as mentioned earlier, it is beyond the scope of this project. It is brought into attention in our Dynamic Hypothesis since it can become an important factor depending on how EPA sets standards and regulations in the future. The sector depicted in Figure 6-2 will show the Model structure as it stands.

6.2.1 Model Structure : Visual Layout

The figure below shows a snapshot of the environmental sector. The circles represent parameters that may be constants or dependant relations or equations. The boxes are stocks, which represent accumulations of any sort. Here, the model primarily investigates the accumulation of Carbon Dioxide. The thin arrows relate parameters, stocks and flows by linking them through equations. The thick arrows with taps are flows that indicate the rate at which a particular change is occurring to the stock. The variable names are self explanatory. However, a more detailed explanation of each element with equations where necessary will be provided next.

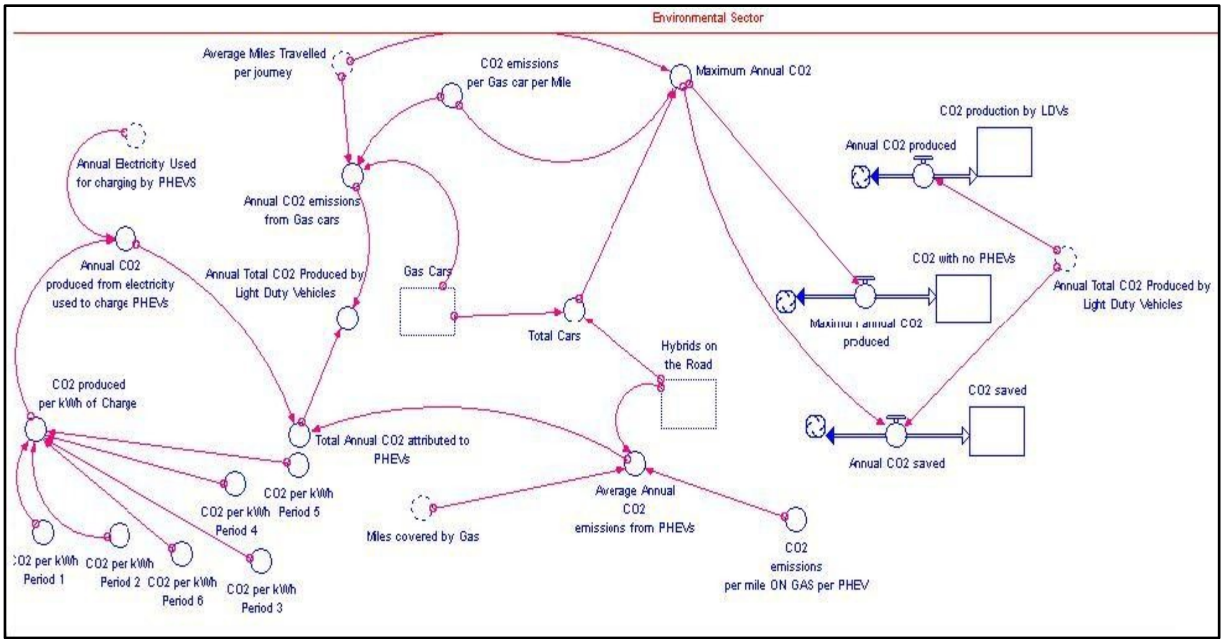

Figure 6-2 Environmental Sector Model

6.2.2 Variable Definitions and Setup

This section will describe all stocks, flows and parameters. Detailed descriptions of parameters are provided here. The next section will describe detailed stock flow relationships.

1. ***Annual Electricity used for charging by PHEVs:*** This represents the amount of electricity in kWh used to charge PHEV batteries annually in Massachusetts. The daily charging energy by PHEVs is given by the product of Hybrids on the Road and Effective average battery capacity, assuming batteries are fully charged every day. Multiplying this figure by 365 will give us the annual energy used in charging by PHEVs.
2. ***Annual CO_2 produced from electricity used to charge PHEVs:*** The generation of electricity that is used to charge PHEVs produces electricity as bi product. Therefore, this parameter takes into account the CO_2 produced that can be attributed to charging a PHEV.
3. ***CO_2 produced per kWh of charge:*** If PHEVs are charged during different times of the day, different amounts of CO_2 are produced since the electricity is generated from different sources at different times. This is a sensitivity parameter. When a certain charging period is investigated, the parameter is multiplied by 1 and the rest of the values are multiplied by 0 (turned off). This will allows us to see what period produces the least CO_2 for charging PHEVs. In the equation described above, PHEVs are assumed to have been charging only during period 1.

4. ***CO_2 emissions per mile ON GAS per PHEV:*** The PHEVs operation comprises of two modes: It runs on electricity as long as the battery can provide charge and it switches to its internal combustion engine when the battery runs out of charge. There is no CO_2 emission when running on electricity. However, when running on its internal combustion engine it produces CO_2 emissions.
5. ***Miles covered by Gas:*** This parameter is defined in the Battery Sector. In essence it is the number of miles that the PHEV will run on its internal combustion engine. This will depend on its electricity mileage and the average journey distance.
6. ***Average Annual CO_2 emissions from PHEVs:*** The number of Hybrids on the road multiplied by CO_2 emissions per mile per PHEV gives the CO_2 emissions per mile by all PHEVs. This number multiplied by the number of miles covered by gas gives the total amount of CO_2 produced by PHEVs daily. Finally, this number multiplied by 365 gives the annual figure.
7. ***Total Annual CO_2 attributed to PHEVs:*** This parameter is the sum of the annual CO_2 produced by PHEVs due to electricity used in charging and PHEV emissions while running on gas.
8. ***Average Miles traveled per Journey:*** Journey distances vary from individual to individual. We have taken typical average values for weekends, weekdays and occasional long journeys and averaged them for this parameter.
9. ***CO_2 emissions per gas car per mile:*** This parameter is the amount of CO_2 emitted on average in Kg per mile of a gas car.
10. ***Annual CO_2 emissions from gas cars:*** This parameter signifies the amount of CO_2 emitted by Gas cars in one year given the current conditions. It depends on the number of gas cars , average journey distance and the amount of CO_2 emitted per mile by a gas car.
11. ***Gas Cars:*** This is a stock that is taken from the Hybrids sector. It represents the current number of gas cars on the road. The detailed stock flow relationship of this parameter has been established in the preliminary model description provided in the previous Project's documentation. In essence, the inflow to the stock is gas car sales. The gas car sales is dependent on total demand for cars and the sale of PHEVs. The outflow is dependent on the number of gas cars and the useful life of a gas car which determines the scrappage rate. This stock is important in our sector since it will help us compute the amount of CO_2 emissions attributed to gas cars, and light duty vehicles in general.
12. ***Hybrids on the Road:*** This stock represents the number of Hybrids on the road. The detailed stock flow structure is discussed in the previous Project's documentation. The inflow to this stock is the Sale of Hybrids and the outflow is the scrappage rate. Both depend on multiple factors, including the all important Hybrid Appeal. This stock is important to our sector because it will help us calculate amounts of CO_2 attributed to PHEVs and light duty vehicles in general.
13. ***Total Cars:*** Total cars is a parameter that is representative of the total number of cars on the road in that particular year. It is essentially a sum of Hybrids on the road and gas cars. This parameter is essential in calculating or predicting the worst case CO_2 emissions that could occur if all cars were internal combustion engine cars.

14. ***Maximum Annual CO_2 and Maximum Annual CO_2 produced:*** The maximum annual CO_2 is a parameter that represents the worst case scenario of CO_2 emissions assuming all cars present on the road are gas cars. This parameter was designed to be a performance measure parameter. Since this parameter represents the maximum annual CO_2 produced in that year, it is also equal to maximum annual CO_2 produced (the inflow to the CO_2 with no PHEVs stock). As can be seen from the equation of this parameter given below, the average miles travelled per journey times the CO_2 emissions per gas car per mile gives the daily CO_2 emissions of a gas car. Multiplying this figure by the total number of cars and 365 gives the annual CO_2 produced in kg assuming all cars were gas cars.

6.2.3 Stock flow Structures

Stock-flow structures of CO2_production_by_LDVs

1. CO2_production_by_LDVs(t) = CO2_production_by_LDVs(t - dt) + (Annual_CO2_produced) * dt
2. INIT CO2_production_by_LDVs = 0

INFLOWS:

3. Annual_CO2_produced = Annual_Total_CO2_Produced_by__Light_Duty_Vehicles

Stock-flow structures of CO2_saved

4. CO2_saved(t) = CO2_saved(t - dt) + (Annual_CO2_saved) * dt
5. INIT CO2_saved = 0

INFLOWS:

6. Annual_CO2_saved = Maximum_Annual_CO2-Annual_Total_CO2_Produced_by__Light_Duty_Vehicles

Stock-flow structures of CO2_with_no_PHEVs

7. CO2_with_no_PHEVs(t) = CO2_with_no_PHEVs(t - dt) + (Maximum_annual_CO2__produced) * dt
8. INIT CO2_with_no_PHEVs = 0

INFLOWS:

9. Maximum_annual_CO2__produced = Maximum_Annual_CO2

There are five stocks in total in our environmental sector. Only three of them need be defined, since the gas cars and Hybrids on the road stocks have been defined previously.

CO_2 production by LDVS: This stock represents the amount of CO_2 that is produced in total as the years progress after the introduction of PHEVs. There is only one inflow to this stock, and this is the annual CO_2 production by light duty vehicles and this has been defined above. This stock is meant to be a performance measure, where the lower the value of this stock over the model run time, taken to be 50 years by default for the system, the more favorable the conditions are for the environment. Thus, by varying sensitivity parameters, the model can predict which conditions will allow for the achievement of the lowest possible CO_2 production over 50 years.

CO_2 Reduced: This stock is another performance measure element. It represents the amount of CO_2 reduced due to the introduction of PHEVs. In general, gas cars produce more CO_2 than PHEVs. Therefore, when PHEVs that take the place of gas cars in the total fleet population, there will be less CO_2 produced in total. This stock represents exactly how much CO_2 has been prevented from entering our atmosphere over the model run time of 50 years. The data from this stock is valuable for many areas since the amount of CO_2 prevented from entering the atmosphere can become substantial. When performing sensitivity analyses, the higher the value of this stock the more favorable and noteworthy the conditions are. Finally, this will result in recommendations on how to achieve these conditions.

Annual CO_2 reduced: This is a performance measure parameter and is an inflow to CO_2 reduced (described below). The introduction of PHEVs that replace gas cars will effectively result in a lower CO_2 generation than CO_2 generation assuming only gas cars on the road. Therefore, the difference in the maximum possible annual CO_2 production and annual total CO_2 produced by light duty vehicles will provide the annual CO_2 reduced due to the introduction of PHEVs. This parameter is one of the important performance measures implemented since it will indicate the amount of CO_2 reduced over the years as PHEVs proliferate.

Total annual CO_2 produced by light duty vehicles: This parameter is the sum of the total annual CO_2 emissions by gas cars and the total annual CO_2 produced that can be attributed to PHEVs. This figure important because it will indicate how cars are producing CO_2 in Massachusetts .

Annual CO_2 produced: This is an inflow into the CO_2 produced by light duty vehicles stock. It is equal to the annual CO_2 produced by light duty vehicles.

6.2.4 Parameters in model

10. Annual_CO2__produced_from_electricity_used_to_charge_PHEVs = Annual_Electricity_Used_for_charging_by_PHEVS*CO2_produced__per_kWh_of_Charge

11. Annual_CO2_emissions_from_Gas_cars = Gas_Cars*CO2_emissions__per_Gas_car_per_Mile*Average_Miles_Travelled_per_journey*365

12. Annual_Total_CO2_Produced_by__Light_Duty_Vehicles = Total_Annual_CO2_attributed_to_PHEVs+Annual_CO2_emissions_from_Gas_cars

13. Average_Annual__CO2_emissions_from_PHEVs = Hybrids_on_the_Road*CO2__emissions__per_mile_ON_GAS_per_PHEV*Miles_covered_by_Gas*365

14. CO2__emissions__per_mile_ON_GAS_per_PHEV = .483
15. CO2_emissions__per_Gas_car_per_Mile = .3166
16. CO2_per_kWh_Period_1 = 0.2473866
17. CO2_per_kWh_Period_2 = 0.505949
18. CO2_per_kWh_Period_3 = 0.505949
19. CO2_per_kWh_Period_4 = 0.722135
20. CO2_per_kWh_Period_5 = 0.505949
21. CO2_per_kWh_Period_6 = 0.247387
22. CO2_produced__per_kWh_of_Charge = 0*CO2_per_kWh_Period_1+0*CO2_per_kWh_Period_2+0*CO2_per_kWh_Period_3+0*CO2_per_kWh_Period_4+0*CO2_per_kWh_Period_5+1*CO2_per_kWh_Period_6
23. Maximum_Annual_CO2 = Average_Miles_Travelled_per_journey*CO2_emissions__per_Gas_car_per_Mile*Total_Cars*365
24. Total_Annual_CO2_attributed_to_PHEVs = Annual_CO2__produced_from_electricity_used_to_charge_PHEVs+Average_Annual__CO2_emissions_from_PHEVs
25. Total_Cars = Hybrids_on_the_Road+Gas_Cars
    Equation 25

7. Sensitivity Analysis and Experiments

7.1 Sensitivity Analysis: Oil Market Sector

With the use of system dynamics and the model that has been already set up, this project will test various sensitive and crucial parameters to see their results on the system as a whole and specifically on the major system variables.

The sensitivity tests conducted in this section will relate to the effects and changes brought about by factors in the oil market and industry. The results will be organized by means of performance measures which will give a detailed understanding of the behavior of the system. These results will then be used to develop proposals and recommendations as well as giving further insight of what could happen to the introduction of PHEVs under these different scenarios.

The sensitivity parameters that will be tested are as follows:

1. Miles_as_electric
2. Oil_price_per_bbl
3. Average_Journey
4. Avg_Miles_per_gallon

The performance measures that will be reviewed include the following stocks and flows:

Stocks:

1. Oil_price_per_bbl
2. Hybrids on the Road
3. Gas Cars
4. Total Gas Saved

Flows:

1. Gas price at pump
2. $ saved per mile
3. $ saved per year

The stocks and flows will be analyzed on case by case scenario and for each experiment, those which are most relevant will be included. In each experiment, the default model parameter will be tested, followed by varying the parameter and observing the changes in the appropriate performance measure.

7.1.1 Experiment 1: Varying miles_as_electric

Miles_as_electric is a parameter which represents the number of miles that a PHEV can run as a purely electric vehicle. An increase in this parameter leads to a decrease in gas usage and also increases the appeal for hybrid cars. Ideally, this value should increases over the years with technological growth. The default value of this parameter is set to 40 miles, and will be tested for 30 miles, 50 miles and an optimistic value of 70 miles.

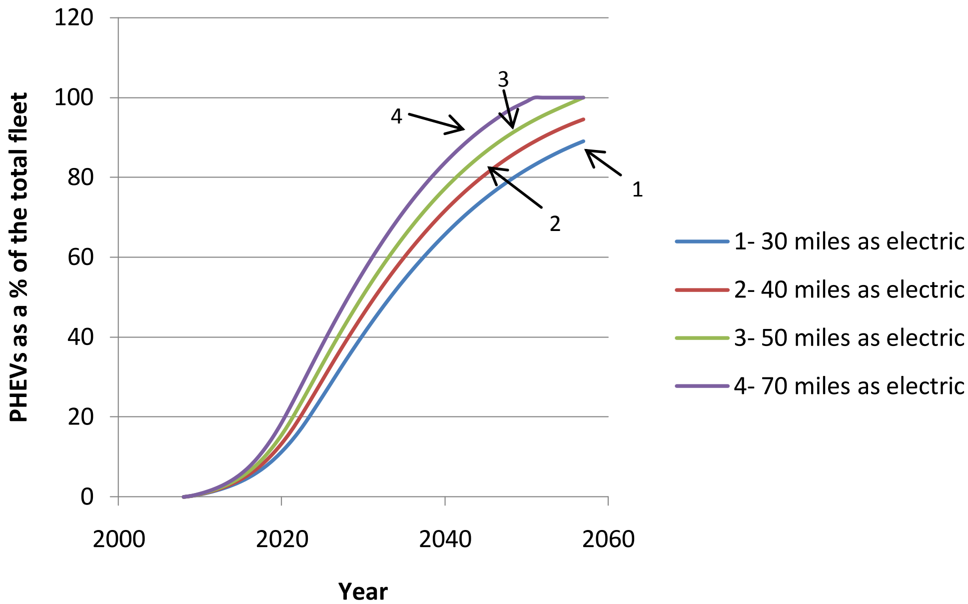

Figure 7-1 PHEVs as a % of the total fleet in Massachusetts versus time with miles as electric as a sensitivity parameter

As the number of miles that a hybrid can run as on pure electricity increases, the number of hybrids, as expected, also grow at a faster rate. This is due to an increase in the appeal for hybrid cars.

Table 7-1 Dollars saved per year for a PHEV owner with miles as electric as a sensitivity parameter

Miles on Electric	Avg. $ saved per mile	Avg. Miles travelled in a year	$ saved per year
30	0.0628	12500	785
40	0.1082	12500	1352.5
50	0.1144	12500	1430
70	0.1208	12500	1510

The total amount of money a PHEV owner can save per year also goes up as the number of miles on electricity of a PHEV goes up. This behavior is expected since the running cost of an electric car is cheaper than that of a gas car and as the miles that a PHEV can give as an electric goes up, the cost of running in comparison to a gas car is reduced.

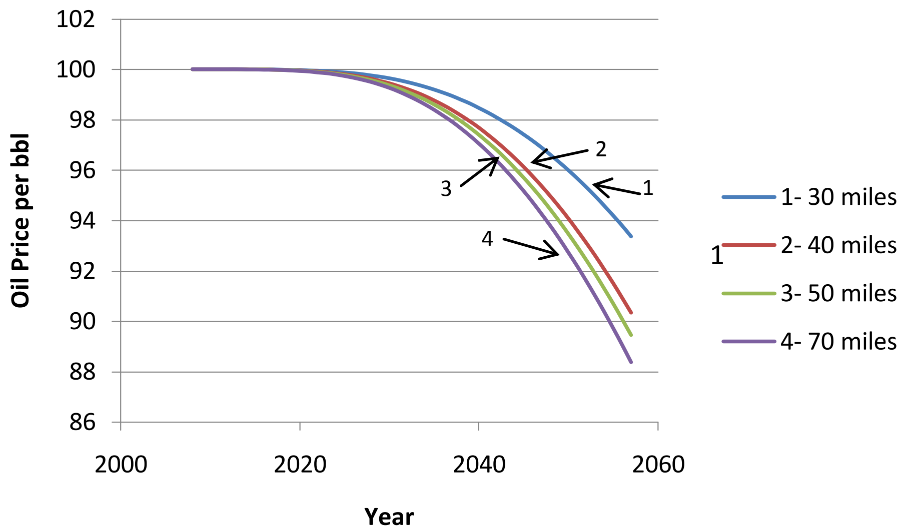

Figure 7-2 US Oil price per bbl versus time with miles as electric as a sensitivity parameter

The oil price per bbl drops more quickly for the case where there is a larger number of miles on electric for the PHEV. This is because of a reduced requirement of gasoline and hence a reduction in demand and import. It is important to note that we begin with an assumed oil price of $100/bbl for each case.

Analysis:

With an increase in the number of miles that a PHEV runs as a purely electric vehicle, the dependence on gas goes down. As a result, the cost to operate a PHEV tends to depend more on the charging cost and less on the cost from when the PHEV runs as a gasoline vehicle. With this decrease in cost, the owner of a PHEV will save more money unless the gas cost goes below a certain level – this is depicted in Table 7-1.

Also, since there is a decrease in this operating cost, it becomes more beneficial to own a PHEV and hence the hybrid appeal also goes up. With this increase in hybrid appeal, the PHEVs also tend to grow at a faster rate, as shown in Figure 7-1.

Figure 7-2 depicts a decrease in oil price with an increase in the number of miles that a PHEV runs as a purely electric vehicle. This is because an increase in these electric miles reduces the use of gasoline and hence decreases the oil consumption. With a decrease in consumption, there is more of an inventory than that which is required and hence the prices go down.

These results clearly show that an increase in the no. of miles on electricity is good for both the PHEV owner and the gas car owner as well.

7.1.2 Experiment 2: Varying Oil_price_per_bbl

The last 12 months or so have seen great changes in gas and oil prices. Crude oil prices have ranged from around $80 to $140 and consequently, gas price have reached as high as $4.5/gallon. Oil prices vary not only with the demand from the automobile industry but also due to a variety of reasons such as international pressures, wars, etc. However, it seems like the gas prices usually follow the trend of oil prices. Over the last couple of weeks or so, oil prices have been falling again and are now close to $90/barrel. In this section, the base oil price will be taken to be $100/barrel and it will be varied to an upper limit of $125/barrel and a lower limit of $75/barrel and see the dynamic changes that come about in the system.

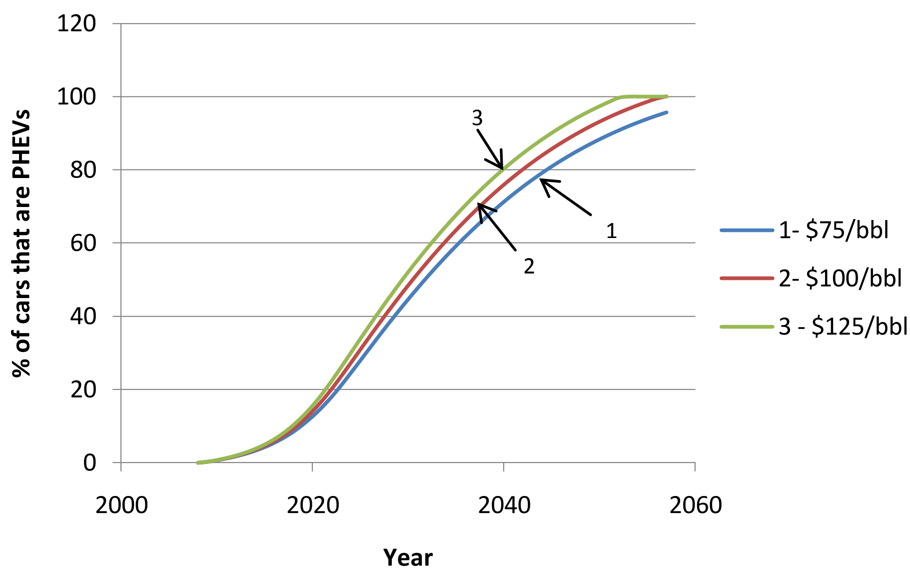

Figure 7-3 PHEVs as a % of the total fleet in Massachusetts versus time with oil price per bbl as a sensitivity parameter

It is seen that for higher initial oil price or gas price cases, PHEVs tend to grow faster. This comes directly from the relation between oil prices and gas prices. With higher oil and hence gas prices, the appeal for PHEVs goes up and hence the behavior which is depicted in Figure 7-3.

Table 7-2 Dollars saved per year for a PHEV owner with oil price per bbl as a sensitivity parameter

Initial Oil Price per bbl	Avg. $ saved per mile	Avg. Miles travelled in a year	$ saved per year
75	0.0852	12500	1065
100	0.1082	12500	1352.5
125	0.133	12500	1662.5

It is seen that for higher initial oil prices hence gas prices, the amount of money saved in terms of operation of a PHEV is higher and hence more beneficial for the owner.

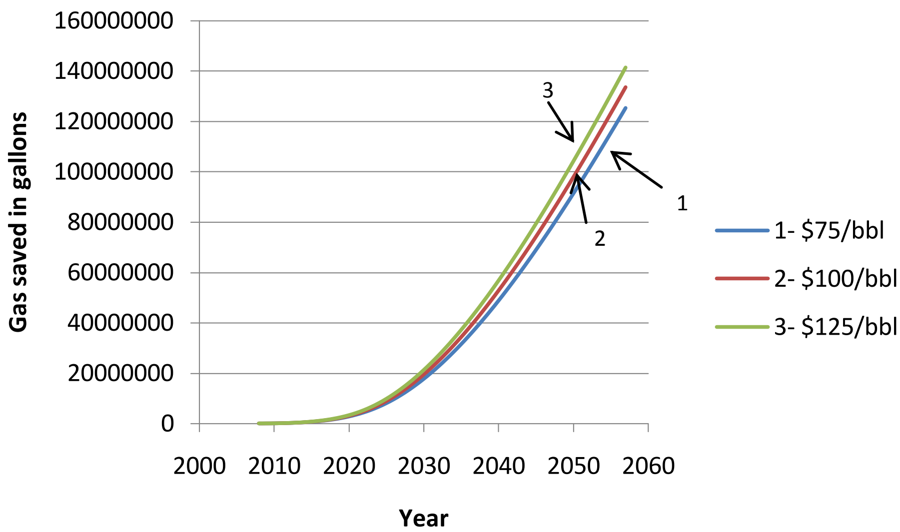

Figure 7-4 Cumulative gas saved versus time with oil price per bbl as a sensitivity parameter

Figure 7-4 shows that as the cost of oil increases, the total amount of gas that is saved increases. This is because people will tend to drive less and will buy more fuel efficient vehicles, such as PHEVs.

Analysis:

With an increase in the initial oil price per barrel there is an instantaneous increase in the initial gas price as well. This increase in gas price makes it more beneficial to buy a PHEV since one could save more money in the long run. As a result, there is an increase in the operational cost of a gas car and hence an increase in the appeal for hybrid cars. This leads to an increase in the number of PHEVs as seen in Figure 7-3.

Also, with this increase in gas price, there is an increase in the gas car operational cost and consequently more money is saved in using a PHEV. This is depicted in **Error! Reference source not ound.** which indicates that one could save about $1650 a year if oil prices were to increase to $125 and about $1350 a year with the current oil prices.

With this increase in the number of PHEVs for higher priced cases, a larger replacement of the gas car fleet takes place and hence the dependence on gas decreases. This decrease is shown in Figure 7-4. The total gas saved for the $125 case decreases the dependence on oil in MA by about 2%. This is not a small number considering that we are only talking about a percentage of consumer gas cars being replaced by PHEVs.

7.1.3 Experiment 3: Varying Average_Miles_per_Gallon

Average_miles_per_gallon is a variable that represents the miles per gallon that an average gas car is able to obtain. An increase in this factor leads to an increase in the efficiency of both plug-in hybrids when they function as gas cars and traditional gas cars. The increase in the efficiency of gas cars decreases hybrid appeal and slows down the growth of hybrids. The average miles per gallon value is set to 25 mpg and is tested for 35 mpg and 45 mpg.

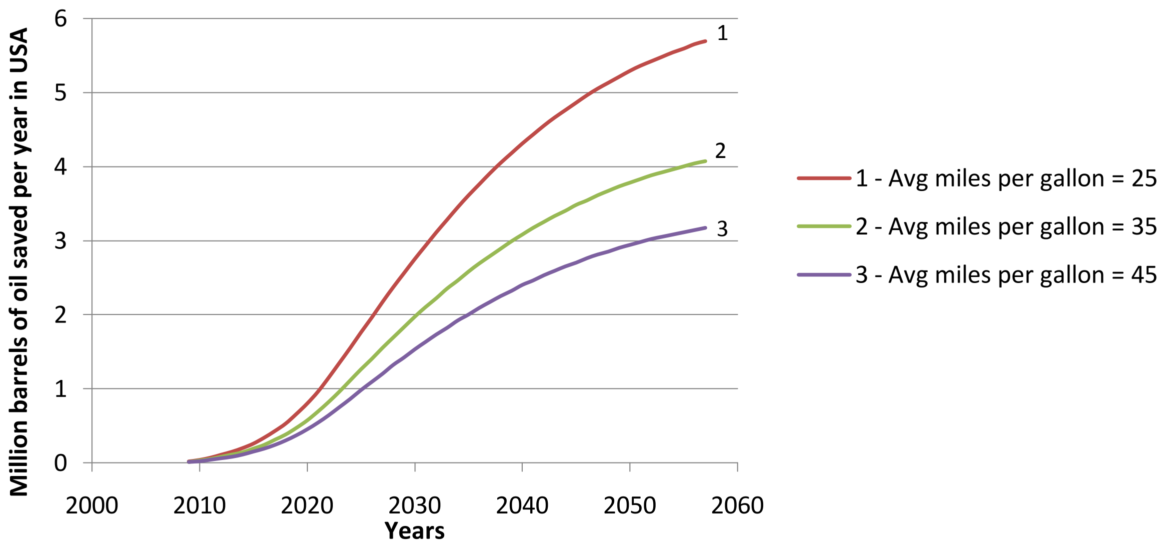

Figure 7-5 Million barrels of oil saved per year in USA versus time with Average_miles_per_gallon as a sensitivity parameter

As Average miles per gallon increases, the appeal for a gas car increases. As a result there are a much larger number of gas cars and hence the barrels of oil saved tends to fall.

Table 7-3 $ saved per year for a PHEV owner with Average_miles_per_gallon as a sensitivity parameter

Average miles per gallon	Avg. $ saved per mile	Avg. Miles travelled in a year	$ saved per year
25	0.1082	12500	1352.5
35	0.0696	12500	870
45	0.0454	12500	567.5

It is observed that as Average_miles_per_gallon rises, the Avg $ saved per mile tends to fall since the cost per mile while running as gas also decreases. Thus, the total $ saved per year by a hybrid owner decreases.

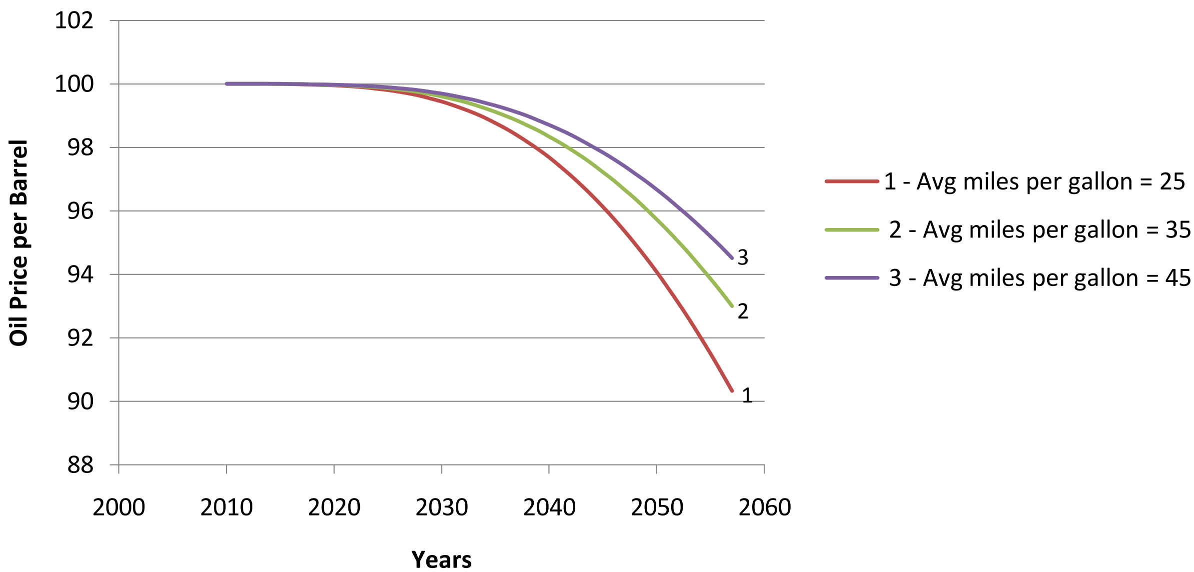

Figure 7-6 US oil price per bbl versus time with Average_miles_per_gallon as a sensitivity parameter

It can be observed that for a higher average miles per gallon, the fall in the oil price per barrel is smaller and thus oil is more expensive for a bigger average miles per gallon.

Analysis:

As average_miles_per_gallon increases, the efficiency of gas cars increases and their operational cost comes down. This holds back the people from switching to hybrid's and the growth in hybrids is thus smaller. Since it is cheaper to run a gas car, they are more popular and gas consumption increases. This results in a lesser number of barrels saved and as the fall in demand for oil is smaller, the fall in the oil price per barrel is also smaller.

It can also be seen that as Average_miles_per_gallon rises, the $ saved per year decreases. This is because $ saved per mile falls which means that the operational cost of a gas car falls and thus the difference in cost between operating a gas car and a PHEV starts to fall. Thus, in terms of running costs, gas cars and PHEVs are almost equal.

7.1.4 **Experiment 4: Varying Taxes_Distribution_Refining_Cost**

Taxes_Distribution_refining_costs include the three different costs. Taxes are charged by the government per gallon of gas. Distribution costs are costs that go into distributing the oil to different pumps around the country. Refining costs are incurred by the refinery when gasoline is extracted from crude oil. Research showed that the combined cost of these three parameters is about $1[32],

[32] (Factors in the retail price of gas - CNN)

independent of the price of oil. The rest of the price of gas is directly proportional to the Oil price per barrel.

Since oil prices depend on international conditions and demand, the government can use the taxes parameter to adjust the price of gas to a suitable value to match domestic demand and supply. Since the normal value for this parameter was initially set to $1, it was tested for values of $0.50 and $2.

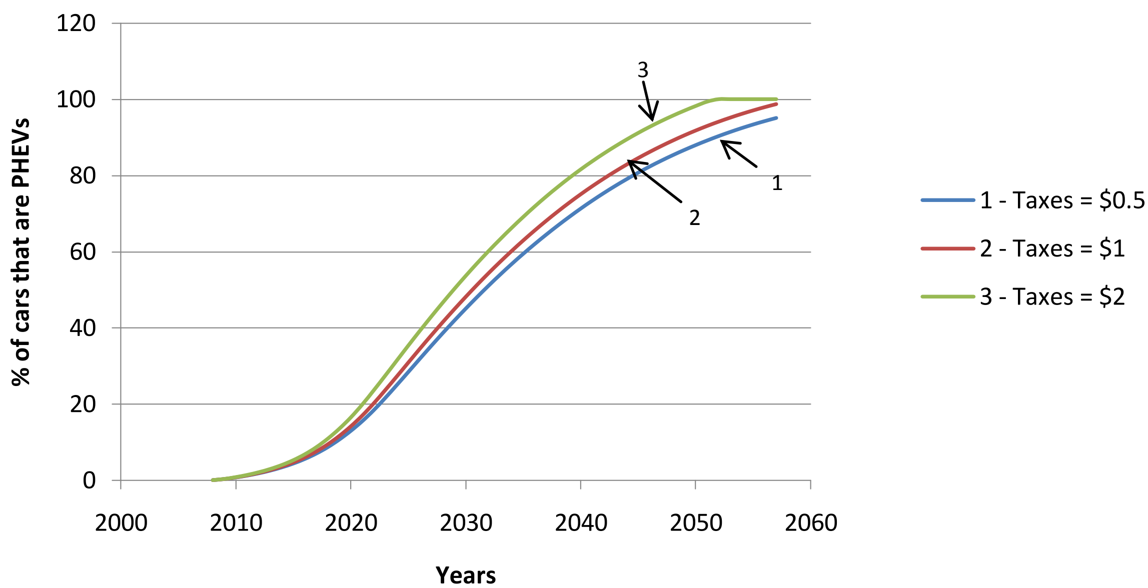

Figure 7-7 PHEV growth versus time with Taxes_Distribution_Refining_Cost as a sensitivity parameter

Figure 7-7 shows how PHEVs rise with higher taxes. The higher the taxes, refining costs and distribution costs, the more the gas prices. Hence, an increase in the demand for hybrids.

Table 7-4 $ saved per year for a PHEV owner with Taxes_Distribution_Refining_Cost as a sensitivity parameter

Taxes, Distribution & Refining cost	Avg Gas Price at Pump	Avg. $ saved per mile	Avg Miles travelled in a year	$ saved per year
$0.50	2.9478	0.0882	12500	1102.5
$1	3.4444	0.1082	12500	1352.5
$2	4.4394	0.1484	12500	1855

Table 7-4 how an increases in taxes, distribution and refining costs effect the gas price at pump and the average $ saved per mile. Using average miles travelled in a year by a person, the table shows the total $ saved per year by a person.

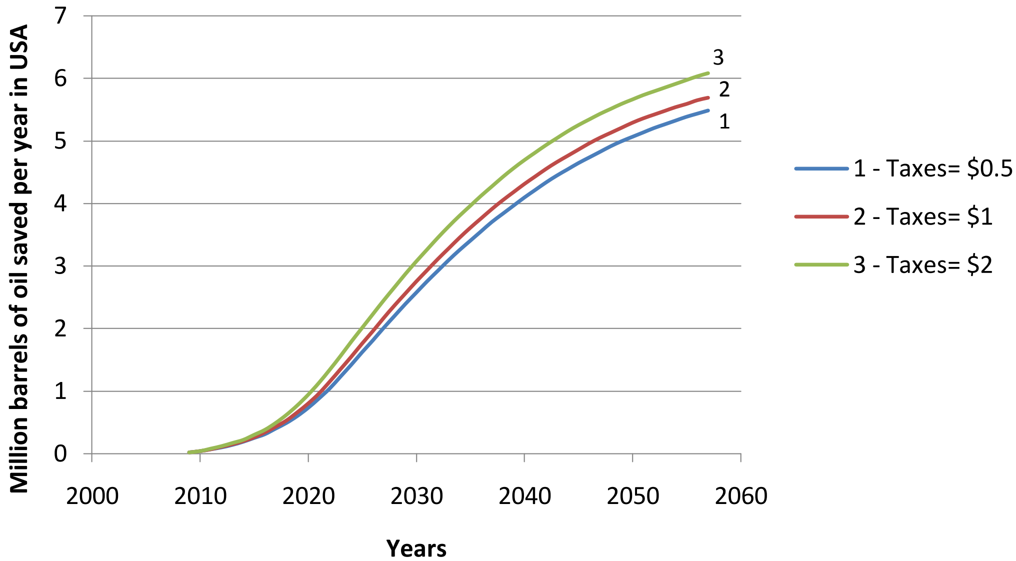

Figure 7-8 Million barrels of oil saved versus time with Taxes, Distribution and Refining costs as a sensitivity parameter

Figure 7-8 shows how savings are effected with increased taxes refining and distribution costs. The higher these costs are, the more barrels of oil being end up saved.

Analysis

As taxes, distribution, and refining costs increase, the first thing that is affected by it is the gas price at pump. As these taxes and costs increase, gas prices are directly and immediately effected by them. The spike in gas prices effect hybrid appeal directly and causes it to increase. This causes a greater growth in PHEVs as can be seen in Figure 7-8 above.

Increase in taxes, distribution and refining costs also cause an increase in the $ saved per mile. This results in significant additional savings for the owner of an PHEV, which increase with every increase in taxes, distribution and refining costs.

Also, with PHEVs increasing at a faster rate for each additional change, million barrels of oil saved also sees a faster change.

7.2 Sensitivity Analysis: Environmental Sector

In this section, sensitivity analyses will be conducted to see how variables, stocks and flows of interest will change as certain parameters are changed. The parameters being changed are chosen such that policy recommendations can be proposed. In other words, the parameters may represent controllable elements in the real world, so if a change in that parameter brings about a change that is desirable then a policy can be recommended with respect to that parameter. This will become clear as more experiments are performed. Policy recommendations will be given that promote the favorable results in real life.

The sensitivity tests conducted in this section will only relate to CO_2 production trends. In other words, the evaluation of the effect of the sensitivity tests will be given in terms of the performance measures that have been described in the model definition section- 6.2.2. The aim is to identify parameters such that CO_2 levels of the environment are effectively kept at a minimum by the proliferation of PHEVs.

The sensitivity parameters that will be investigated are as follows:

- PHEV battery technology factor
- PHEV engine technology factor
- Hybrid car useful life
- Hybrid Capital Cost
- CO_2 produced during charging periods 1-6

The performance measures that will be analyzed are the following stocks and flows:

Stocks:

- CO_2 Reduced
- Hybrids on the Road as a % of Total

Flows:

- Annual CO_2 produced by LDVs

Graphs of these stocks and flows will be plotted and analyzed. For control graphs (usually blue and labeled with a number 1), default parameter values will be used unless otherwise mentioned. It should also be noted that the charging period for CO_2 used by default is charging period 1.

7.2.1 Experiment 1: Varying PHEV battery technology factor

Battery technology factor is a parameter that acts a multiplier, changing the PHEV performance characteristics. An increase in the battery technology factor will increase battery life and battery capacity. It is nominally set to 1, and this value will be changed to 2 then reanalyzed. The following graphs depict the results.

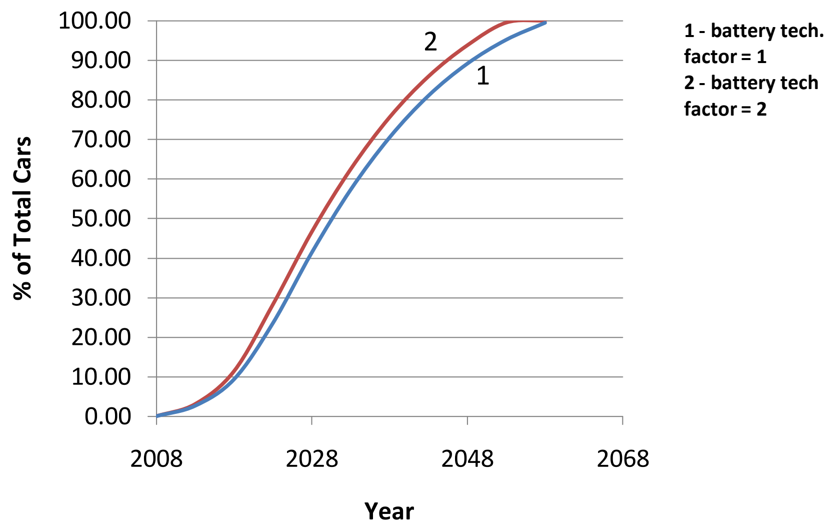

Figure 7-9 Hybrids as a % of Total cars in Massachusetts versus time with battery technology factor as a sensitivity parameter

Figure 7-9 shows that eventually, PHEVs would replace gas cars completely by 2053 in the case of increased technology factor. The nominal value of technology factor shows a slower growth. The increased technology factor causes more rapid proliferation of PHEVs.

Table 7-5 Annual CO2 production by all cars with battery technology factor as a sensitivity parameter

Metric Tonnes of CO2 Produced Annually by Fleet (x 10^3 kg)		
Time	Battery Technology Factor = 2	Battery Technology Factor = 1
2008	21,609,533.00	21,609,533.00
2013	21,509,442.93	21,609,531.25
2018	21,241,159.24	21,413,121.42
2023	20,698,651.76	20,914,921.62
2028	20,110,174.07	19,858,393.90
2033	19,601,043.77	19,529,854.06
2038	19,177,738.64	19,341,861.04
2043	18,843,158.90	19,350,745.47
2048	18,587,796.34	19,555,171.35
2053	18,401,364.64	18,942,845.95
2058	18,105,366.75	18,485,716.72

Table 7-5 shows that the annual CO_2 production (in metric tonnes) would decrease substantially over the next 50 years.

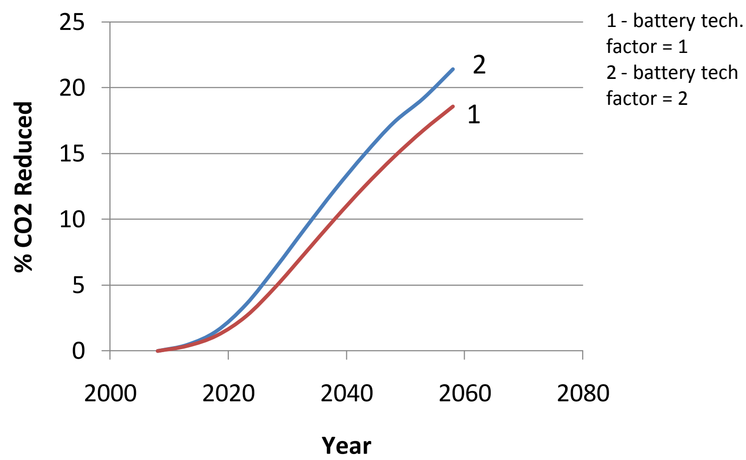

Figure 7-10 Total CO2 reduced as a % of the total CO2 produced in Massachusetts versus time with battery technology factor as a sensitivity parameter

The CO_2 reduced as a % of projected annual CO_2 production (assuming all gas car fleet) increases slowly in the first 15 years and then increases almost linearly until the year 2058 for increased technology factor.

Analysis:

An increase in battery technology factor equates to an increase in battery life and battery capacity at the same time in the model. Therefore, electricity mileage and battery replacement costs fall and consequently increase hybrid appeal. A similar complementary behavior is exhibited by gas cars as their numbers fall much quicker due to PHEVs replacing them much faster.

Carbon dioxide levels at the end of 50 years due to LDVs are lower due to increased PHEV numbers. The amount of CO_2 that is saved is also substantially larger in this case as PHEVs increase in numbers. The environmental advantage that is attained by improving battery technology and prices is thus clearly depicted by our model.

Since one PHEV produces less CO_2 annually on average than a gas car does annually, the behaviors depicted by the above graphs can be understood.

7.2.2 Experiment 2: Varying PHEV engine technology factor

PHEV engine technology factor is nominally set to 1. Changing the engine technology factor effectively increases the electricity mileage that a PHEV gets on average. The effect of this on CO_2 production is observed from the graphical results we have obtained from our model.

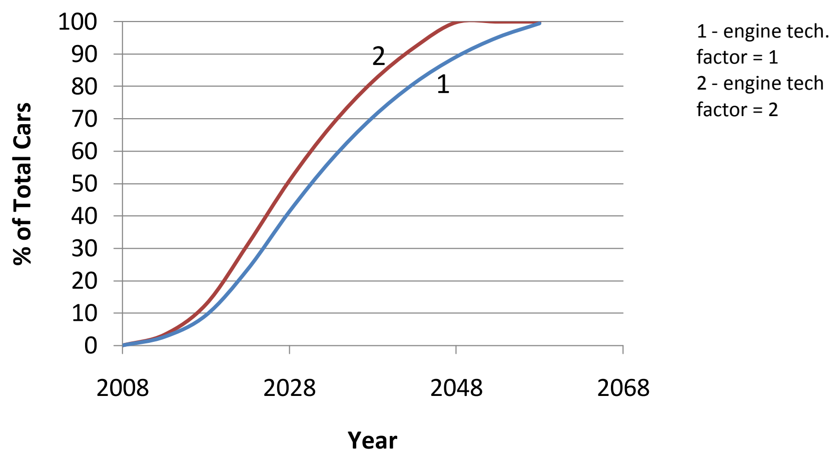

Figure 7-11 Hybrids as a % of Total cars on the road in Massachusetts versus time with engine tech. factor as a sensitivity parameter

As Figure 7-9 shows, the number of PHEVs increase slowly for the first 18 years and then more rapidly until 2048 when the completely replace gas cars.

Table 7-6 Annual CO2 production by all cars with engine tech. factor as a sensitivity parameter

	Metric Tonnes of CO2 Produced Annually by Fleet (x 10^3 kg)	
Time	Engine Technology Factor = 2	Engine Technology Factor = 1
2008	21,609,533.00	21,609,533.00
2013	21,363,925.13	21,609,531.25
2018	20,663,169.06	21,413,121.42
2023	19,285,700.90	20,914,921.62
2028	17,813,810.72	19,858,393.90
2033	16,545,458.94	19,529,854.06
2038	15,511,919.53	19,341,861.04
2043	14,714,967.48	19,350,745.47
2048	14,128,821.22	19,555,171.35
2053	14,964,987.95	18,942,845.95
2058	15,854,406.94	18,485,716.72

The annual CO_2 produced by the fleet also decreases substantially over the next 50 years, almost a 20% reduction in CO_2 emissions.

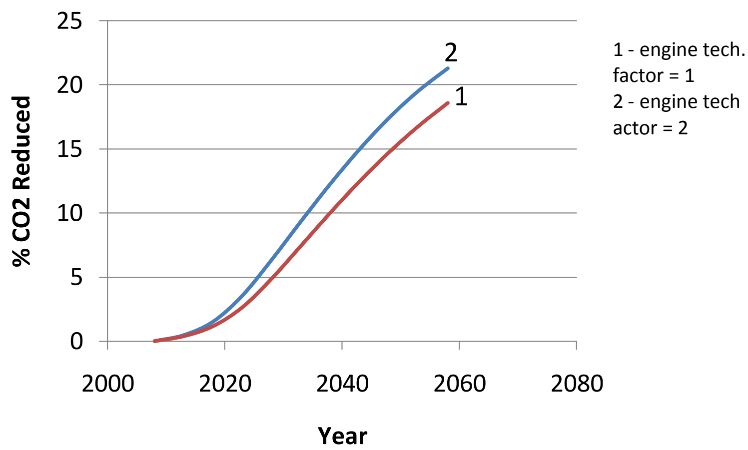

Figure 7-12 Total CO2 reduced as a % of Total CO2 produced in Massachusetts versus time with engine tech. factor as a sensitivity parameter

A favorable growth pattern that starts out slowly and then more rapidly is shown by the line labeled 2. The model predicts that 21 % of the annual CO_2 produced by gas cars will be saved by increasing technology factor to 2.

Analysis:

The behaviors above arose due to increasing the engine technology factor, which equates to increasing the efficiency of PHEVs in terms of mileage. If the electricity mileage increases on a PHEV, the operating costs for running a PHEV also decrease. This will consequently increase Hybrid Appeal. An increase in Hybrid Appeal will cause faster growth of PHEVs and thus a quicker replacement of gas cars. Since gas cars produce more CO_2 on average than PHEVs annually, we can see that CO_2 levels go down at the end of 50 years with increased PHEV numbers.

Therefore, the conclusion of this sensitivity test is that increases in PHEV engine efficiency will lead to reductions in CO_2 emissions due to more rigorous proliferation of more efficient Hybrids.

7.2.3 Experiment 3: Varying Hybrid Car useful life

In this sensitivity test, we changed a PHEV's average useful lifetime from 20 to 40 years. This would mean that the average PHEV stays on the road for longer, hence PHEV population is predicted to increase assuming nothing else changes. The following graphs and table summarize our results.

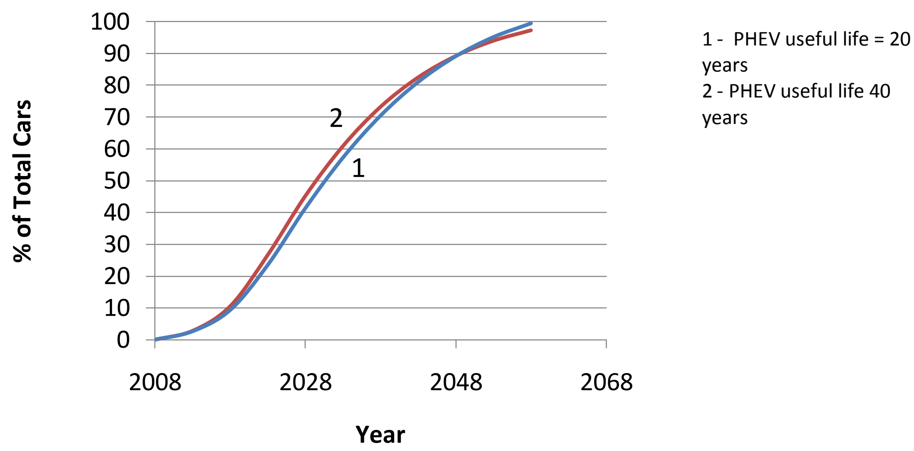

Figure 7-13 Hybrids as a % of Total Cars on the road in Massachusetts versus time with PHEV useful life a sensitivity parameter

As the line labeled 2 shows, PHEV growth is sustained. However, the PHEVs do not completely replace gas cars by the end of 50 years. The growth is seen to be slower than that of the graph labeled 1.

Table 7-7 Annual CO2 produced in Massachusetts by all cars with PHEV useful life as a sensitivity parameter

	Metric Tonnes of CO2 Produced Annually by Fleet (x 10^3 kg)	
Time	Hybrid Car Useful Life = 40 Years	Hybrid Car Useful Life = 20 Years
2008	21,609,533.00	21,609,533.00
2013	21,411,671.53	21,609,531.25
2018	20,867,899.77	21,413,121.42
2023	19,731,958.84	20,914,921.62
2028	18,425,186.09	19,858,393.90
2033	17,309,100.88	19,529,854.06
2038	16,421,748.26	19,341,861.04
2043	15,750,419.38	19,350,745.47
2048	15,259,514.60	19,555,171.35
2053	14,908,883.30	18,942,845.95
2058	14,666,249.93	18,485,716.72

The annual CO_2 produced by the fleet, however, does decrease quite dramatically (almost 35 % this time).

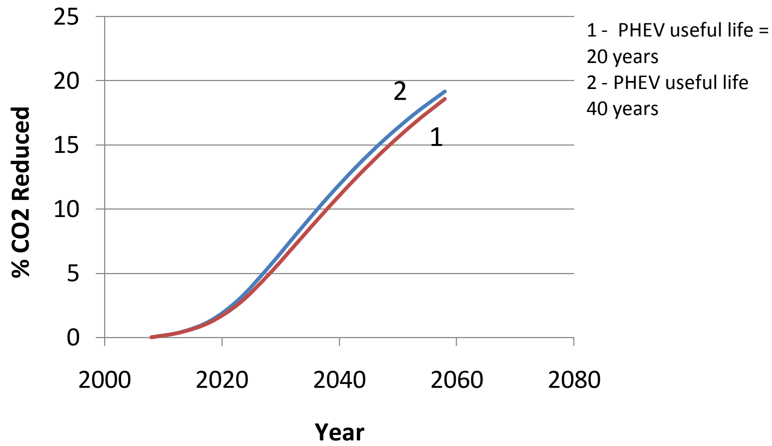

Figure 7-14 Total CO2 reduced as % of Projected Total CO2 versus time with PHEV useful life as a sensitivity parameter

The CO_2 reduced over 50 years is around 19% for the line labeled 2. This is not as high as the other sensitivities. Line 1 is seen to follow line 2 quite closely. This suggests that the effect of Hybrid car useful life is not very significant when considering the percentage of CO_2 reduced.

Analysis:

Hybrid car useful life increases the number of Hybrids on the road. However, this change is not very substantial relative to the changes brought about by other sensitivity parameters such as battery and engine technology factors.

From a modeling standpoint, it can be inferred that the hybrids useful life does not help the proliferation of Hybrids as strongly as factors that affect Hybrid Appeal directly do. This makes sense since how long a car will last for an individual will most likely not be a motivating force for purchasing a Hybrid as much as a factor such as price or mileage will affect it.

Thus, our conclusion is that Hybrid car useful life may increase the proliferation of Hybrids by allowing more Hybrids to stay functional during a given period of time. However, this does not lead to a substantial increase in PHEVs and thus the beneficial impact on the environment by the reduction of CO_2 emissions is not as profound.

7.2.4 Experiment 4: Varying Hybrid Car Capital Cost

One of the most important concerns with the proliferation of PHEVs is their feasibility. Currently as the technology stands, the price of a PHEV is quite high. In our model, a sensitivity where the initial price is listed as 40000 USD, and then changed to 20,000 USD will be conducted. As the price decreases, it is expected that PHEVs will sell a lot faster. This will allow for their proliferation and lead to an effect on the environment in terms of atmospheric CO_2 levels. The following are the results of these sensitivity runs. Run 1 (in blue) shows the behavior when the price is initially set to 20,000USD. Run 2 (in red) shows the behavior when the price is reduced to 10,000 USD, or half the initial price.

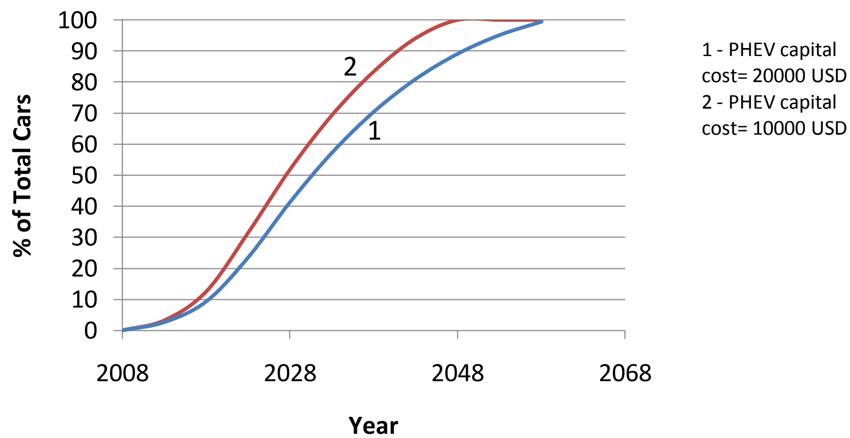

Figure 7-15 Hybrids as % of Total Cars on the road in Massachusetts versus time with PHEV capital cost as a sensitivity parameter

As Figure 7-15 shows, PHEVs proliferate slowly and then quite rapidly for both graphs 1 and 2. By the year 2046 the PHEVs almost completely replace gas cars if capital cost is reduced from 20,000 USD to 10,000 USD.

Table 7-8 Annual CO_2 produced by all cars with PHEV capital cost as a sensitivity parameter

Metric Tonnes of CO2 Produced Annually by Fleet (x 10^3 kg)		
Time	PHEV capital cost = 20,000 USD	PHEV capital cost = 10,000 USD
2008	21,609,533.00	21,609,533.00
2013	21,369,339.92	21,609,531.25
2018	20,675,669.17	21,413,121.42
2023	19,264,345.42	20,914,921.62
2028	17,741,540.12	19,858,393.90
2033	16,431,919.84	19,529,854.06
2038	15,371,288.17	19,341,861.04
2043	14,559,433.07	19,350,745.47
2048	14,393,786.13	19,555,171.35
2053	15,366,378.02	18,942,845.95
2058	16,376,299.08	18,485,716.72

Table 7-8 shows that the total annual CO_2 emissions decrease substantially. However, the decrease in annual CO_2 production is not as significant as we have seen in experiment 3.

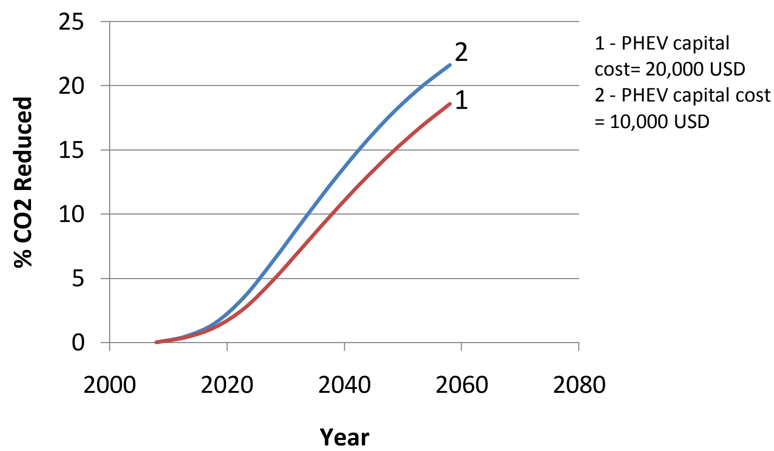

Figure 7-16 Total CO_2 reduced in Massachusetts as a % of Projected Total versus time with PHEV capital cost as a sensitivity parameter

The total CO_2 reduced over the 50 years starts out quite slowly and then grows quite rapidly for both graphs. At the end of 50 years we see that the total CO_2 reduced is almost 22% of the projected total by reducing capital cost.

Analysis:

A reduction in the price of PHEVs is seen to reduce levels of CO_2 to a good extent from our results above. This is understood in terms of the model as increased Hybrid Appeal due to Capital Cost appeal increasing. An increase in Hybrid Appeal causes the sale of Hybrids to occur more frequently, and thus hybrids proliferate faster. This allows more hybrids to replace gas cars and since PHEVs are responsible for a lower amount of CO_2 per vehicle annually than gas cars, more CO_2 can be saved.

Therefore, the conclusion of our sensitivity test is that a price reduction of PHEVs can be expected to produce a favorable impact on our environment by preventing more CO_2 from entering our atmosphere.

7.2.5 Experiment 5: Charging PHEVs at different times of the day

PHEV batteries need to be charged when the battery charge is depleted. Charging times during the day has a significant impact on the amount of CO_3 that is generated from generation plants. This is because electricity is generated from sources that produce different amounts of CO_2 at different times of the day.

The following sensitivity runs will depict how charging at different times of the day will produce different amounts of CO_2. This information will give insight as to what charging period will generate the least CO_2.

The tables below show how the CO_2 reduced as a % of Total Projected CO_2 production changes over 50 years as different charging periods are adopted.

Table 7-9 % CO_2 reduced using charging period 1

Year	CO2 reduced as % of CO2 produced by all-gas car fleet
2008	0
2013	0.38
2018	1.17
2023	2.65
2028	4.90
2033	7.46
2038	10.04
2043	12.50
2048	14.75
2053	16.79
2058	18.60

Table 7-10 % CO_2 reduced using charging period 2

Year	CO2 reduced as % of CO2 produced by all-gas car fleet
2008	0
2013	0.17
2018	0.50
2023	1.14
2028	2.11
2033	3.21
2038	4.32
2043	5.38
2048	6.35
2053	7.23
2058	8.01

Table 7-11 % CO_2 reduced using charging period 3

Year	CO2 reduced as % of CO2 produced by all-gas car fleet
2008	0
2013	0.17
2018	0.50
2023	1.14
2028	2.11
2033	3.21
2038	4.32
2043	5.38
2048	6.35
2053	7.23
2058	8.01

Table 7-12 % CO_2 reduced using charging period 4

Year	CO2 reduced as % of CO2 produced by all-gas car fleet
2008	0
2013	-0.017
2018	-0.053
2023	-0.121
2028	-0.223
2033	-0.340
2038	-0.457
2043	-0.569
2048	-0.671
2053	-0.764
2058	-0.847

Table 7-13 % CO_2 reduced using charging period 5

Year	CO2 reduced as % of CO2 produced by all-gas car fleet
2008	0
2013	0.16
2018	0.50
2023	1.14
2028	2.11
2033	3.21
2038	4.32
2043	5.38
2048	6.35
2053	7.23
2058	8.01

Table 7-14 % CO_2 reduced using charging period 6

Year	CO2 reduced as % of CO2 produced by all-gas car fleet
2008	0
2013	0.38
2018	1.17
2023	2.65
2028	4.90
2033	7.46
2038	10.04
2043	12.50
2048	14.75
2053	16.79
2058	18.60

Analysis:

The amounts of CO_2 generated for each charging period is repeated here for convenience:

Table 7-15 Different amounts of CO_2 produced/kWh in Massachusetts due to charging at different times of the day (kg/kWh)

	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
Total CO2/kWh	0.247	0.506	0.506	0.722	0.506	0.247

Charging periods 1 and 6 have the same values. Charging periods 2,3 and 5 also have the same values. However, charging period 4 has the highest value and is not equal to any of the other values.

As can be seen from the tables above, the highest amount of CO_2 reduced annually as a percentage of projected total CO_2 produced over the next 50 years is shown to be generated by charging periods 1 and 6. These essentially equate to charging at night or near midnight.

The values in the table for charging period 4 show negative values. This should be interpreted as a contribution, rather than a reduction, in the amount of CO_2 generated. The negative values thus mean that more than the projected annual CO_2 will be generated if this charging period is adopted.

8. Conclusions and Recommendations

This project aimed to determine the impact of the proliferation of plug-in hybrid electric vehicles into the Massachusetts transportation industry. Specifically, it addresses 1) whether PHEVs are a green transportation solution 2) how the domestic and foreign oil markets will affect PHEVs 3) under which conditions PHEVs will be most prosperous in Massachusetts.

1. In Massachusetts electricity is generated mostly from natural gas and nuclear power which are clean sources of energy. Taking into account vehicle efficiencies and miles traveled per kilowatthour, this project has proven that electricity used to operate PHEVs result in 22% fewer carbon emissions than the use of gasoline directly in traditional vehicles after 50 years. When PHEVs are charged during off-peak hours (between 8 p.m. and 4 a.m.) electricity is being generated from nuclear, hydro electric and natural gas sources which produce low carbon emissions. PHEVs are only environmentally unfavorable under strained conditions where charging is done during peak hours of demand, particularly between 12 p.m. and 4 p.m., or when vehicles are continually operated for extended trip lengths.
2. Light duty vehicles have a 42% share in the total US oil consumption. Sensitivity analysis shows that the introduction of PHEVs will help bring down that figure and within 50 years, the US will end up saving about 6 million barrels of oil annually. It is also shown that higher oil prices will spur the growth of PHEVs and result in more oil savings, thereby decreasing oil import costs. Due to this lower demand, oil prices will fall by about 10%. Overall, PHEVs will prove to be a very viable alternative for transportation needs of Americans and for the state and will eventually replace the gas car fleet within 50 years.
3. There are several situations under which PHEVs will successfully be implemented into the Massachusetts transportation system. First, technological advances will have great and widespread impact. As battery capacity and motor efficiencies are increased, allowing for average trips to reach up to 75 to 100 miles per charge, appeal will increase as well. Similarly, if the average trip length is reduced, the same effect was observed. As newer, cleaner power plants and alternative fuel generation technologies arise, PHEVs will become increasingly appealing. Because of this green appeal, the drive toward adoption can be intensified through external sources such as government subsidies for the purchase and proper use of PHEVs. It is recommended that the EPA adopts a system which creates subsidies based on the carbon output of vehicles as opposed to the overall vehicle efficiency. Lastly, due to the increased electricity usage during off peak hours, it is also recommended that National Grid strongly considers creating a reduced rate system for households which charge vehicles at night.

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10. Index

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