



# Impact of Plug-in Hybrid Electric Vehicles on the Local Electric Grid

*An Interactive/Major Qualifying Project Report*

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*In partial fulfillment of the requirements for the*

*Degree of Bachelor of Science*

*By*

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## **Abstract**

The following document has been prepared in partial fulfillment of the requirements as a Bachelor of Science at Worcester Polytechnic Institute. The authors, Kazim Naqvi and Timothy Yee, are submitting this document as an Interactive Qualifying Project/Major Qualifying Project in lieu of the above mentioned requirements. Kazim Naqvi is a Mechanical Engineering Student at WPI belonging to the class of 2010. Timothy Yee is a student at WPI majoring in System Dynamics and belonging to the class of 2008.

The authors will be trying to address the possible impact of the advent of Plug-In Hybrid Vehicles (PHEVs) in Massachusetts. With National Grid as a sponsor, the authors will aim to address the impact on the electricity distribution sector and National Grid as a whole. In order to do this, the authors will study the time variation of daily electric demand for Massachusetts, which has been provided by National Grid.

According to this data, the authors decided to implement policies that only permit the charging of PHEVs during periods of low electric demand. This has two advantages: firstly, it puts fewer loads on the local electric grid and does not require investment in additional electricity generation or distribution; and secondly, the electricity used for PHEVs' charging will then come from cleaner and renewable energy sources such as nuclear and hydro-electric power generators.

To do the same, the authors will be utilizing Systems Dynamics Modeling as the basis for experimentation. System Dynamics is a unique field that combines engineering with social science and serves as a tool for making appropriate managerial decisions. Its advent in the 1950s has enabled the development of forecasting models that inform policy and decision makers of the impact/effect of their policies if implemented in a given system. The authors have also decided to use System Dynamics Modeling because the system (comprising of PHEVs and gas cars on the road, distribution equipment for National Grid, and daily electric demand variation) is dynamic and contains several test parameters that can be changed to study the overall behavior of the system.

The results of various modeling, research, and sensitivity exercises conducted during the course of this project show that PHEV's do take off and attain a sustainable value, as was the desired outcome. The impact on National Grid is minimal and the daily electric demand variation does not change significantly. On the finance side, the costs/expenses involved for launching PHEV's successfully (both upfront and long-term) are minimal. However, this will only occur if the right policies and procedures are followed by National Grid, the government, and the consumers.

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# 1. Introduction

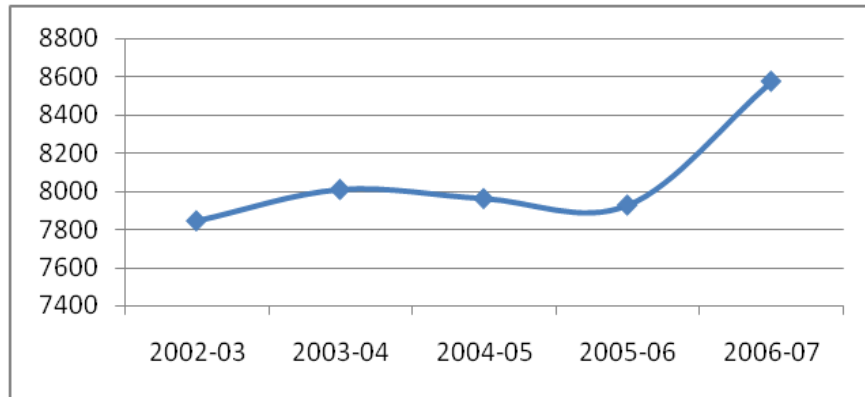
## 1.1. Problem Definition and Background

The post 21<sup>st</sup> century era has seen an incredible change in world resources and environment, which has directly affected the entire human race. The gradual realization of the existence of serious problems such as global warming and the inevitable depletion of non-renewable energy resources has necessitated a drive towards intensive research and strategies to bring forth solutions that are often radical in nature. This drive has fueled a dynamic game of global politics, which has several effects on the problems as well as their solutions. The world today is dynamic; it changes every day, with every change influencing several other changes in a vast network of feedback loops. This project is a humble attempt to assess a very small part of the world dynamics. The overall **goal** of conducting this research project will be to understand some of the transportation problems facing the world today and evaluate the feasibility of a particular solution to these problems. The **vision** that this project aims to achieve is a positive contribution to the world in general which makes it a better place to live in. *(For a comprehensive outline, please see Section 2.3. Goals and Objectives)*

National Grid is a well recognized for-profit organization – operated as a regulated monopoly, which distributes electricity to consumers in the North Eastern part of the United States. The Massachusetts division of National Grid is the sponsor for this project, and hence the research shall be based on how to introduce positive policy changes to this organization. The chief solution to the problem previously mentioned that this project will address is the development of alternative energy vehicles. This study deals with the Plug-in Hybrid Electric Vehicle (PHEV) as a viable option to be adopted by consumers in an attempt to solve the problem of global warming and the diminishing energy resources.

This project will ultimately assess the impact of PHEV's on the state of Massachusetts, paying particular attention to its effect on National Grid. Since PHEVs rely on grid-based electricity as their primary energy source, it is incumbent upon decision makers in National Grid to understand the effect of PHEV penetration on their power grid. The annual average electric demand has shown a continually increasing trend in Massachusetts over the past few years due to longer and hotter summers and the consequent prolonged usage of air conditioners and other temperature regulatory equipment. The increased demand is also evident from the following graph of demand variation for residential consumers over the last five years.





**Figure 1-1 Growth in electric demand from 2002-07 for residential customers**

This is usually an additional and unforeseen cost for National Grid, which forces them to use low efficiency, less economical power stations to prevent load shedding and compensate for the additional peak demand. An increase in the electricity demand during peak hours due to the introduction of PHEVs would be very undesirable for the power generation companies and would raise the cost of electricity they sell to the National Grid.

The primary purpose of this project will thus be the development of a dynamic model which will enable various decision makers to predict the maximum sustainable amount of PHEV's, and plan electricity supply accordingly. The resulting question that will be answered upon completion of this project is:

**“What will be the impact of plug-in hybrid electric vehicles on the power distribution system in Massachusetts?”**

In answering this question, several factors that affect the predictably of the growth of PHEV's shall be studied. Some of these factors will be dealt with in greater detail, as they have a more significant effect on the dynamics of growth in PHEVs. These include the effects by and on National Grid, the environment and the consumers of PHEVs. The specific research data and statistics prevalent to the model will be inputted such that the model's results simulate real-world behavior. Many secondary factors that do not have significant impact on the overall dynamics of the system will also be introduced at various intervals into the model in order to create an accurate model. This will serve as an integral part of the sensitivity analysis (see Section 5.1. Sensitivity Analysis for further details). For the compilation of the results, a final system model will incorporate all of the major factors as well as some of the minor factors affecting the growth of PHEVs. This project outline is geared towards the achievement of the above explained vision and goals for all people involved in the project.

## **1.2. Alternative Propulsion Technologies for Vehicles**

Plug-in Hybrid Electric Vehicles (PHEVs) are only one type of alternative energy vehicles. In the model, the primary focus will be on PHEVs and traditional internal combustion engine vehicles. This

does not imply that the model will be the correct and the only outcome in the future; rather, it is just the primary focus of this project and an underlying assumption.

There are many other types of alternative propulsion technologies in development and all are offering a solution to alleviate the country's severe dependence on petroleum based fuels and help reduce the subsequent green house gases that are produced. Before deciding to analyze PHEVs as a solution to the energy crisis, other options currently in development must be considered. This section gives a brief description of the current and projected technologies that have been suggested by researchers and scientists.

### 1.2.1. Fuel Cells

Fuel cells are another form of alternative technology currently being explored for adaptation in vehicles. They are similar in comparison to an electric vehicle in that they are operated by electric motors. They differ, however, in that they rely on fuels cells as opposed to batteries as a method of electricity supply into the motors. Fuel cells undergo a chemical reaction that requires a constant input of reactants, whereas a battery uses a chemical to store a charge. For use in cars, fuel cell vehicles (FCVs) have been projected to be in production around 2010, the same time frame as the PHEVs.<sup>1</sup>

The current model for these FCVs will use hydrogen as a source of power and will produce water and heat as direct byproducts of the chemical reaction. The current fuel cell technology will support a total mileage of 200 or less. They will convert hydrogen into electricity through the flow of electrons through the cell, which can then be used to operate electric motors. Fuel cells have been rated at 50% efficiency. Half of the energy produced is in the form of usable energy (electricity), while the remainder is dismissed to the environment as heat. Hydrogen powered FCVs claim to offer true zero emission vehicles during the physical operation of the vehicle.<sup>2</sup>



Figure 1-2 Honda's concept hydrogen fuel cell car

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<sup>1</sup> (U.S Department of Energy)

<sup>2</sup> (The California Fuel Cell Partnership)

The FCV in development, however, faces a major hurdle of Hydrogen fueling and delivery. In order to facilitate the transformation from gas to fuel cell vehicles, the fuel infrastructure must be in place. Currently no such infrastructure is developed in Massachusetts, hindering anyone that operates such a vehicle to an extremely limited range. FCVs also face the problem of storage and production of hydrogen. Currently, hydrogen storage is large, bulky and heavy, reducing the effectiveness of the vehicles. In the future, storage solutions might include dissolving hydrogen in metals or small scale hydrogen production within the vehicle from gasoline or other fuels. Producing hydrogen on a large scale is also a major hurdle that must be overcome. It is extremely expensive. Another major concern is the safety related to hydrogen fuel cells. All these factors of storage, production and cost make FCVs an option that is will not be feasible until the technology improves. There might however exist a possibility to develop FCV's fueled by gasoline or ethanol in the short run as it would at least double the gas mileage currently available from the internal combustion engine.<sup>3</sup>

### **1.2.2. Traditional Hybrids**

Traditional hybrids differ from PHEV in that they use a combination of a traditional internal combustion engine and electric motors to produce their power. They currently offer a widespread alternative to a traditional internal combustion engine vehicle. They have the ability to operate with one or both systems in conjunction with each other. Normal city driving is stop and go; the electric motor would be used during this time, saving gas. For longer, consistent periods of use, the ICE would be used to run the vehicle and simultaneously charge the battery.

The traditional hybrids produce their own electricity, with no need to be plugged in. Currently in production around the world, they have established a known customer base. These cars are more fuel efficient than most traditional cars, which is a major draw to the vehicles. Current hybrids models are rated at around 35 miles per gallon (MPG), offering a 10 MPG increase over traditional gasoline vehicles. In addition to the increased fuel efficiency, the infrastructure needed to support this type of technology is regularly available and nothing new has to be added to the transportation infrastructure to accommodate them.<sup>4</sup>

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<sup>3</sup> (U.S Department of Energy)

<sup>4</sup> (Toyota Motor Sales USA Inc.)



**Figure 1-3 Toyota 2008 production Prius**

The main drawback to this alternative is that it still depends on an internal combustion engine for much of its power. This means that they are still dependant on petroleum based oil thus still produce green house gases, although at a decreased rate. In this transition phase, traditional hybrids are currently priced is at \$10,000 greater than a traditional gad vehicle.<sup>5</sup>



**Figure 1-4 Prius Cut away showing both electric motor and gas engine.**

### **1.2.3. Pure Electric**

The idea of a purely electric vehicle has been around for many years. They are very similar to the idea of PHEVs, in that they use electricity to drive motors, but they do not require an internal combustion engine to operate and they run purely on electricity. In the transportation industry, there are many options to this, including solar arrays that would power cars, and battery technology that would store electricity. In theory, these vehicles would pollute even less and would potentially fit the zero emission standards of the government, which in turn will reduce oil dependencies in the future.

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<sup>5</sup> (Toyota Motor Sales USA Inc.)

Pure electric vehicles are optimal, but they face some of the greatest challenges. The current battery technology is insufficient to support a vehicle that operates solely on electricity. They are too heavy, bulky and do not store a charge long enough. These batteries would make the car too heavy and inefficient for practical daily use. The idea of solar powered cars has floated around as well. They too face their limitations in storage and conversion technologies. Some areas of the country only receive limited sun, due to weather and other factors. <sup>6</sup>

In the long run, it seems that the pure electric vehicles have the potential to be accepted, but they require the most investment and also a further research in battery technology and increasing their limited range, in order to become a viable alternative to gas powered vehicles.

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<sup>6</sup> (Heath)

## 2. Project Description

### 2.1. Definition

In order to provide a comprehensive definition of this project, it is necessary to define first the terms that will be referred to frequently in this report. The *variables* studied in this project consist of various factors that govern the demand for the Plug-in Hybrid electric vehicles. These variables dynamically change the behavior of the growth of hybrid plug-ins in the area (the state of Massachusetts). In this case, the *system* comprises of a collection of major and minor variables that are logically and technically connected to the change in the number of operating hybrid plug-ins over a designated period of time. Finally, the proposed *model* is a virtual simulation of this system and its variables which will forecast the change in hybrid plug-in dynamics.

**The project is therefore the design of a *dynamic model* of the previously mentioned *system* and the study of the various scenarios created by it using *computer simulation***

This definition is consistent with the previously mentioned question outlined in the problem definition. The next section, will describe the major system variables, including how they are particularly relevant to the behavior of the model.

### 2.2. Understanding the system variables

In order to understand the complicated system being studies, it is essential to comprehend the significant variables describing its behavior. The following are definitions of all pertinent variables that form the scope of this project.

#### 2.2.1. Hybrid Plug-ins

This variable is defined by the total number of hybrid plug-ins in Massachusetts over an extended period of time, such as 50 years. This quantity can be further broken down into hybrid plug-ins on the road and hybrid plug-ins available for sales, which are dynamically affected by the sales, production, and scraping of hybrids. Production and sales of hybrid plug-ins are also affected by appeal of hybrid plug-ins in the market, since automobile manufacturers and buyers make decisions to produce or buy hybrids according to their appeal in the market.

#### 2.2.2. Traditional Cars

The current norm for transportation in today's society is either gasoline or diesel powered vehicles. In this analysis, these ICE vehicles are directly linked to the increase in PHEVs. As the demand for gas vehicles decreases, demand for the plug-in hybrids will increase. Factors in this analysis include rising gas prices, maintenance costs, annual sales and the number of vehicles in Massachusetts at any particular time.

### **2.2.3. Hybrid Appeal**

This variable is used to model the abstract phenomenon of how attractive PHEVs are as an automotive option. This factor is affected by the capital and operating costs of both PHEVs and traditional cars. It is also affected by the number of each car type on the road. The appeal variable is directly proportional to the sale of hybrids such that if the appeal for hybrids increases, there will be more hybrids sold.

### **2.2.4. kWh Demand and Supply**

Kilowatt-hour (kWh) demand is the amount of electricity that is demanded throughout a 24 hour period by the consumers in Massachusetts. In the model, it has been assumed that the supply capacity can accommodate current demand as well as reasonable overload. It can also be expanded if a sustained increase in load is experienced.

### **2.2.5. National Grid Revenues and Expenses**

Since the growth of the model is restricted to electricity used by PHEVs, the revenues expressed by the model are only due to electricity sold arising from PHEVs. PHEV batteries require charging once they are drained, so consumers will be charging their vehicle batteries and thus using an increased amount of electricity. The additional expenses incurred by National Grid are associated with supplying the additional electricity to home users arising from extra electricity needed to charge PHEVs. The cost associated with buying electricity from generating plants is also incorporated into the system since an increase in electricity demanded and supplied will mean more electricity will need to be bought from generating plants. The overall aim of this sector is to depict the behavior of how *cash* (accumulated profit) will change as a result of electricity usage by PHEVs.

### **2.2.6. Troughs and Peaks for Electricity Demand**

The traditional electric load profile for all consumers in Massachusetts over a twenty-four hour time period has peak electricity consumption between 10 am and 2 pm and the trough, or minimum, during the night hours. This cyclic load profile is inefficient and does not maximize the capabilities of the electricity distribution system. The optimal outcome of the introduction of PHEVs would be to have a nearly constant demand throughout 24 hours of the day, which maximizes the distribution resources. In theory, the implementation of the PHEVs will help to obtain this 'trough filling' result by increasing the electricity consumption during off peak hours via overnight charging.

### **2.2.7. Transformers and Substations**

This section examines the life of the transformers and the associated factors that affect it. In modeling the life of transformers, a better understanding will be developed for how the load curves affect transformer life and the subsequent measures that National Grid might be required to take. This will attempt to predict how the life of the transformer will be affected as more PHEVs come on the road and hence how long the current equipment will last. To do this, a generic transformers and substations will be analyzed as well as daily load curves estimated from previous data.

### **2.2.8. Traditional Car Emissions**

Aside from the ever increasing cost of gasoline, the traditional automobile also emits harmful gases. The primary concern is that the major greenhouse gas carbon dioxide, emitted by the internal combustion engine, will continue to contribute to global warming. By introducing PHEVs, there will be an anticipated decrease in these harmful emissions. In Massachusetts, using electricity is less harmful to the environment per mile driven than the purely gasoline powered vehicles. As the public and lawmakers become more conscious of this environmental impact, this result will help drive demand away from the traditional gas powered car and to the more environmentally friendly PHEV.

### **2.2.9. State/Federal Policies and Regulations**

It is in the best interest of the state and nation as a whole to be conscious of the ways energy associated with the transportation sector of society is supplied and converted from thermal to mechanical or from electrical to mechanical energy. This portion of the model is designed to gauge the impact on PHEVs if certain economic policies are implemented. The rationale behind these policies is simple: a tax credit would be merited if the amount of harmful environmental emissions associated with the operation of the hybrids is less than a gasoline or diesel powered vehicle.

## **2.3. Goals and Objectives**

Any new technology will have a significant and wide spanning effect on society. The implementation of Plug in Hybrid Vehicles is no different. Thus, it is important to understand what the effects of implementing PHEVs will be. This will then give insight into what actions may need to be taken in order to incorporate this new technology into extant systems today and take advantage of the facilities provided by the new technology. System Dynamics modeling is a powerful tool that allows for the understanding of such systems and can give fairly accurate behavioral insight into any changes that the system faces. There are numerous studies and methods of approach that can be conducted based on PHEVs in society. Due to limited time constraints, however, the study will be narrowed down to achieve a specific set of objectives.

The main resource that will be affected by PHEVs is electricity. Of all entities, electricity distribution companies such as National Grid will arguably be affected the most. If PHEVs attain popularity and begin to grow, an additional demand on electricity will be imposed. PHEVs are also likely to grow as gas prices increase and electricity prices remain competitive in relation to gas. National Grid and other distributors will need to account for this growth and prepare themselves to be in a position to meet these increases in demand when if the situation arises. One major endeavor in this project is to forecast this behavior of increase in the electricity demanded per day due to an increasing number of PHEVs in operation.

By taking into account the affect of increased electricity demand on substations and transformers within the model, an understanding has been developed of the relationship between cash acquired by National Grid and the depreciation of transformers used by it. This will give insight as to when capital investment into substations may need to be performed, which may prove useful to companies such as National Grid for planning purposes.



PHEVs are primarily popular due to their environmentally friendly nature. Since they mostly run on electricity, they produce virtually no harmful carbon emissions during their actual operation phase, and significantly less overall (including electricity generation). If PHEVs become popular and replace gas cars on the road, this would equate to a significant reduction of emissions that damage the environment. The model will also be used in an attempt to forecast how emissions will change as PHEVs are introduced and their numbers increase.

## 2.4. 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 the determining 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.

Once the reference mode has been completed, the next step is to build a *dynamic hypothesis*. The dynamic hypothesis represents the overall model. It shows which are 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 minor factors that are not included in the model. 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 leaves 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 be 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. As with all models, this too will be wrong. The end model only represents a single outcome when there are many possibilities.

## 3. Background Research

### 3.1. Plug-in Hybrid Electric Cars

#### 3.1.1. History

The first concept hybrid, XP-883 was introduced in 1969 by General Motors<sup>7</sup>. The term *plug-in* mean that it could be physically plugged into a wall circuit. In the late 1990s, a new initiative was brought about to introduce PHEVs as alternative fuel vehicles to help ease pollution in some major European cities. These concept cars were only prototypes, and were never meant for full production and their cost was nearly double that of a comparable ICE vehicle<sup>8</sup>. Still, the idea remained afloat and many of the major auto industries still expressed interest.

PHEVs prototypes of the past are differentiated from the newly introduced prototypes by a few key factors. Recently, the idea of house hold plug-in, battery types, capacity and the instability of fuel cost, have all driven PHEV popularity to rise. New PHEVs that are planned for production later this year and in the next few years are planned to use lithium-ion batteries. The older models of PHEVs used lead-acid batteries<sup>9</sup>. The lithium-ion batteries offer several distinct advantages over the former, and will be discussed later in this section (3.3.5 Plug-in Hybrid Battery Technology). These PHEVs are designed and marketed to be plugged-in to an ordinary 110-volt household socket to be charge. This was also offered in the XP-883 and the Audio A4, in 220 voltages for the European market, but during their time it was considered a hassle to plug them in.

The final factors affecting today's PHEVs is the recent advent of government policies toward a greener transportation industry along with the sustained increase of fuel cost. Over the past years, fuel prices have ranged greatly. Driving this dramatic shift, crude fuel costs have also risen with oil prices recently, peaking at an all time high of \$105 per barrel<sup>10</sup>. All of these factors ultimately contribute to the rationale behind why PHEVs may be adopted.

#### 3.1.2. PHEVs vs. Gas Hybrids

PHEVs are hybrid electric cars that run on batteries for a limited period, 40 miles, then on combination of an internal combustion engine and batteries for longer period, 400 miles. What makes these types of vehicles different from a current model hybrid is the plug-in aspect. While current model hybrids work in a similar way—batteries for short then an ICE for longer periods—they cannot be plugged in to a wall socket to be charged. The PHEV design focuses more on the battery-only range of these vehicles. They are designated by their battery range as PHEV followed by a number, for example PHEV20 is a PHEV with a battery range of 20 miles. This offers the PHEVs a unique advantage over the current hybrids of a greater battery only range. Like other electrical devices, they can be plugged in

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<sup>7</sup> (Norbye and Dunne)

<sup>8</sup> (Vermie)

<sup>9</sup> (Norbye and Dunne)

<sup>10</sup> (Associated Press)

while stopped during a long road trip without needing to stop at a gas station. The current traditional hybrids rely solely on their ICE to provide power to charge their batteries. PHEVs will have an overall better range because they rely more on these batteries with the ICE as a secondary source of energy and charging.

### 3.2. Electricity Usage

To optimize the usage of the electricity distribution system, it is very important to accurately gauge the supply of electricity according to the electricity demand. To do this, it is important to first understand the cyclic demand profile as it varies throughout the day.

To better cater to the needs of its large variety of clientele, electric utilities have separated the customers into eleven groups according to their major characteristics. Each sector distributes electricity in accordance to its specific demand throughout the day. The sectors are as follows:

R-1: Residential Regular: This sector caters towards general residential customers. The maximum electric supply for this sector does not exceed 2500 kWh per annum per household. The distribution charge per kWh for this sector is 2.52 cents.

R-2: Residential Low Income: This is a minor subsector that has a similar tariff to the R-1 class. However, the rates are subsidized to adjust to the budget of low income households. The distribution charge per kWh for this sector is 0.376 cents.

R-4: Residential – Time-of-use: This sector caters towards residential customers who have an electrical supply requirement exceeding 2500 kWh per year. The tariffs for this class are considerably higher than those for R-1 (6.312 cents per kWh)

G-1: General Service – Small Commercial & Industrial: This sector, as its name suggests, meets the requirements of small-scale industrial and commercial establishments. The distribution charge per kWh for this class is 4.017 cents (note that this is higher than R-1 but lower than R-4 charge)

G-2: General Service – Demand: This sector caters to the electricity demand of large scale industries and commercial establishments. The distribution charge per kWh for this class is \$6.21.

G-3: Time-of-Use: This sector meets the requirements of large scale industries that do not have continuous large electrical demand. Rather, their electrical demand is abrupt and very high. To prevent a payment of excess costs by such organizations during times of low electrical demand, this class has a tariff that only applies when their electrical demand is exceeds 25 MVA. The average distribution charge per kWh for this class is thus \$3.80.

In the analysis, overall electricity demand in conjunction with the individual demand curves will primarily be used for the regular and high income residential sectors. The *Regular Residential* sector, R-1, factors in the average residential customer who consumes no more than 2500 kWh per month, and *Time-of-Use Residential*, R-4, takes into account residencies which consume greater than 2500 kWh per

month. It is a simplifying assumption that the demand for PHEVs will be within these two sectors. For more information on the rates tariff for each class/sector, refer to Appendix D.

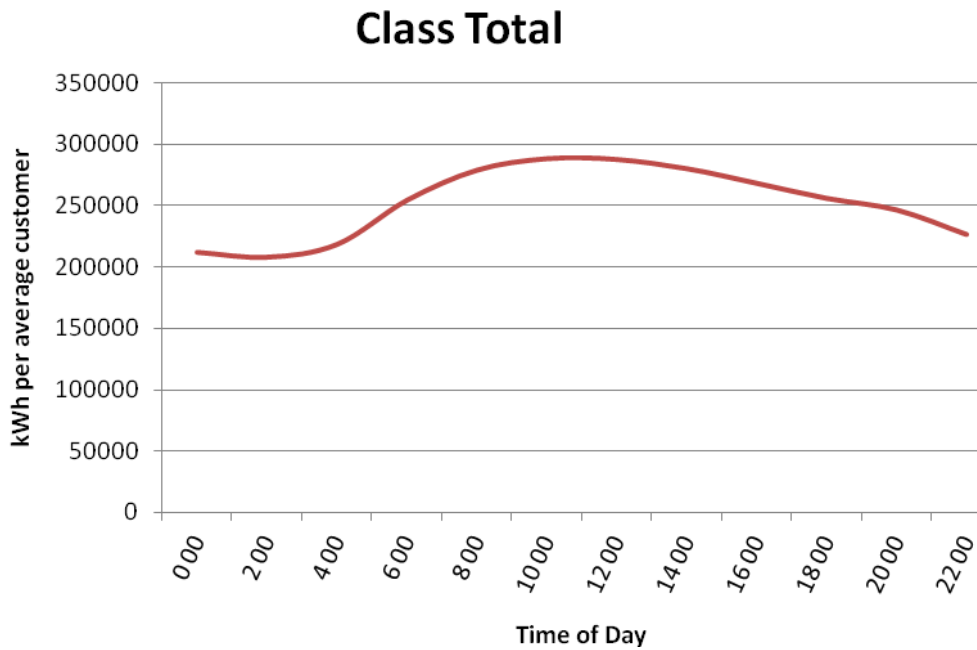


Figure 3-1 Total Industrial Demand. Average from July 2004 – June 2007

The overall demand for electricity has a peak around midday, while creating troughs during the night hours. During the areas of high demand, it is important that the distribution company is able to supply the required amount of electricity to meet this demand. Because of this additional infrastructure needed for this increased capacity to accommodate the peaks, the resources are not being maximized during off peak hours.

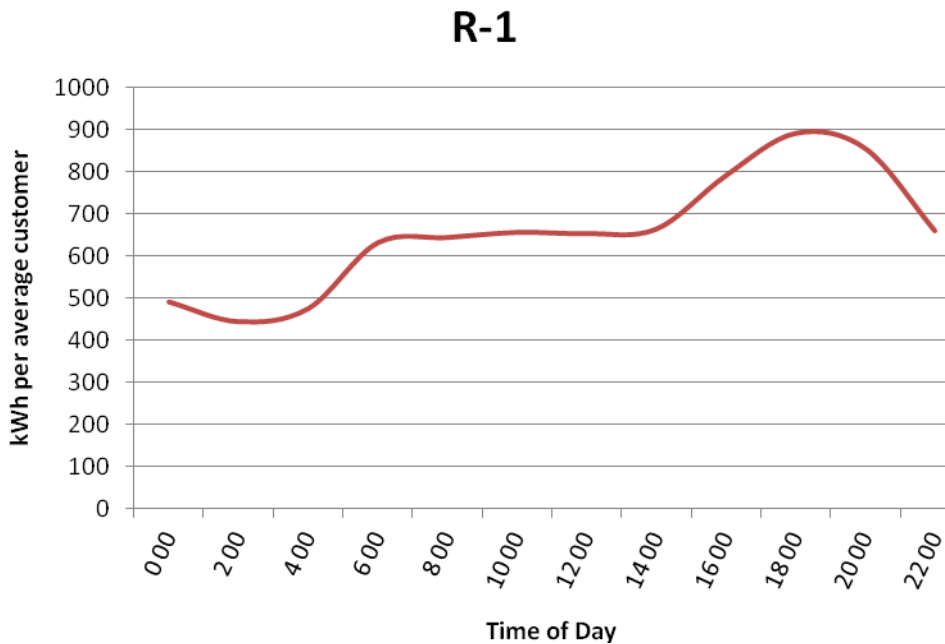


Figure 3-2 Total Residential Demand Profile for R-1. July 2006 – June 2007

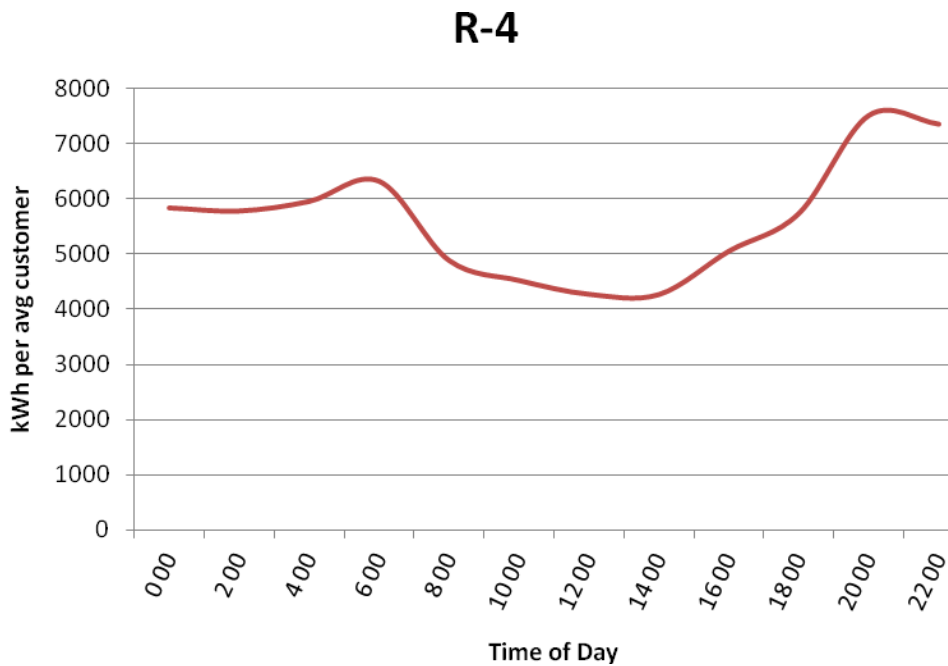


Figure 3-3 Total Residential Demand Profile for R-4. July 2006 – June 2007

For the residential sectors (R-1 and R-4), it is important to take into account the increase in demand over its peaks. Although the overall demand profile in Massachusetts produces a trough at night, the residential sectors are experiencing peaks during the night hours. However, for the purpose of modeling, an assumption has been made that all the substations in Massachusetts are inter-connected.

This means that the additional load generated by hybrids is equally distributed amongst all, not just residential. Also, each substation is assumed to be subject to loads largely influenced by the industrial sector and hence none are focused at looking at a primarily residential supply.

With these underlying assumptions, the conclusion was developed that the advent of hybrid cars will not have a major impact of the life of the transformers in the substations and hence they will continue to function as expected.<sup>11</sup>

### **3.3. Charging Technologies**

#### **3.3.1. The Compressed Air Possibility**

Energy is obtained by the sudden expansion of compressed air. The use of compressed air for storing energy is a method that is not only efficient and clean, but also economical. In 1973 CAES (Compressed Air Energy Storage) installed their first compressed air energy storage plant in Germany, making use of natural underground caves for compressed air storage, taking advantage of the surplus energy produced by the generating plants. Later, similar plants were installed in the United States (Alabama and Ohio).

These plants are designed to operate 24 hours a day; they charge during the night and they discharge during the day. The advantage of these kinds of plants is that they make use of the surplus of electricity (at low cost) by turning it into compressed air stored underground. Later on this energy is used in a turbine generator to help the electricity network during periods of high demand.

CAES was developed in the early 1970s. It uses compressed air to turn a turbine, which in turn, produces electricity. The concept is simple, efficient and clean. Air is forced into an underground cave or mine during off peak hours using a compressor. When electricity is in higher demand, it is released, rotating a turbine and generating electricity. In 1973, the first CAES power plant was built in Germany. The United States would soon follow suite, building similar plants in the years to follow.

On a domestic scale, CAES can be used as an alternative fuel that can be used to power vehicles. This idea can be potentially useful due to a number of reasons. The costs involved to compress the air to be used in a vehicle are less than those involved with a normal combustion engine. As a fuel, air is also vastly more abundant, economical, transportable, storable and nonpolluting. The technology involved with compressed air reduces the production costs of vehicles by 20% because it is not necessary to assemble a refrigeration system, fuel tank, spark plugs or silencers. In comparison to purely battery operated vehicles, which after a while suffer from a reduction in performance from the batteries, the tanks used in a compressed air motor have a longer lifespan.

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<sup>11</sup> These assumptions also form the crux of the recommendations to National Grid. Please see Section 6 for more information.



**Figure 3-4 Tata Motor in conjunction with MDI Air Car**

Nevertheless, there are some disadvantages associated with this technology which have held it back from leading the pack of alternative fuel technology vehicles. For one, there is a limited range due to the current technology available in the market. The air engine suffers from similar problems to hydrogen vehicles in this regard. From an energy standpoint, the compression of air is less efficient than charging a battery with that same energy. Also, while the air engine reduces greenhouse gas emissions from the vehicle, the energy used to compress the air may not come from clean sources. For this reason, the assumption that air cars produce no harmful environmental emissions is not valid. Looking at the entire process, the overall efficiency is approximately one third of that of a comparable electric car.<sup>12</sup>

Currently, there is some sort of experimentation taking place with this technology. Presently, in India, Tata Motors and Motor Development International are completing a joint venture to build a CAES car. The car requires electricity to compress the air and then this compressed air is released to drive the engine of the car. The compression of the air, as mentioned, is driven by an on-board battery. Details of the air-car peg the top-speed at 68 mph, and a range of 200-300 kilometers (up to 186 miles). These tanks containing the compressed air can be refilled at special stations, or using the on-board electric compressor in 3-4 hours.

### **3.3.2. Pneumatic-Hybrid Electric Vehicle**

The idea of using compressed air as an energy vector can, for example, also be applied to a hybrid vehicles. In this case, however, the cylinders function on compressed air and an additional battery which uses electricity to create a vehicle powered solely on electrical-pneumatic propulsion.

A Korean Company, Energin, is currently testing and producing such vehicles. The car uses compressed air when the car needs a significant amount of power, in situations such as starting up the car and acceleration. The electric motor comes to life once the car has gained normal cruising speed (12-15 mph).<sup>13</sup>

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<sup>12</sup> (Electricity Storage Association)

<sup>13</sup> (PES Network)



### 3.3.3. The Fuel Cell Possibility

#### 3.3.3.1 Usage in Cars

Although they are not expected to reach the mass market before 2010, fuel cell vehicles (FCVs) may someday revolutionize on-road transportation. They represent a radical departure from vehicles with conventional internal combustion engines. Like battery-electric vehicles, FCVs are propelled by electric motors. While battery electric vehicles use electricity from an external source (and store it in a battery), FCVs create their own electricity. Hydrogen fuel cells onboard the vehicle creates electricity through a chemical process in which the hydrogen fuel reacts with oxygen from the air.

FCVs can be fueled with pure hydrogen gas stored in high-pressure tanks. They also can be fueled with hydrogen-rich fuels such as methanol, natural gas, or even gasoline, but these fuels must first be converted into hydrogen gas by an onboard device called a "reformer."

FCVs fueled with pure hydrogen do not directly emit any pollutants, only water and heat, while those using hydrogen-rich fuels and a reformer produce a significant amount of the greenhouse gas carbon dioxide. In addition, FCVs can be twice as efficient as similarly sized conventional vehicles and may also incorporate other advanced technologies to increase efficiency.<sup>14</sup>

#### 3.3.3.2 Efficiency

The efficiency of a fuel cell is dependent on the amount of power drawn from it. Drawing more power means drawing more current, which increases the losses in the fuel cell. As a general rule, the more power (current) drawn, the lower the efficiency. Most losses manifest themselves as a voltage drop in the cell, so the efficiency of a cell is almost proportional to its voltage. For this reason, it is common to show graphs of voltage versus current (so-called polarization curves) for fuel cells. A typical cell running at 0.7 V has an efficiency of about 50%, meaning that 50% of the energy content of the hydrogen is converted into electrical energy; the remaining 50% will be converted into heat.

For a fuel cell operated on air (rather than bottled oxygen), losses due to the air supply system must also be taken into account. This refers to the pressurization of the air and adding moisture to it. This reduces the efficiency significantly and brings it near to the efficiency of a compression ignition engine. Furthermore fuel cells have lower efficiencies at higher loads. The tank-to-wheel efficiency of a fuel cell vehicle is about 45% at low loads

#### 3.3.3.3 Cost

Chief among the problems associated with fuel cells is how expensive they are. Many of the component pieces of a fuel cell are costly in of themselves. In order to be competitively priced (compared to gasoline-powered vehicles), fuel cell systems must cost \$35 per kilowatt. Currently, the projected high-volume production price is \$110 per kilowatt.

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<sup>14</sup> (Today)

### **3.3.4. The Norwegian HyNor Solution**

The Norway HyNor Project is developing rapidly between the cities of Oslo and Stavanger. This project will provide a sensible means of providing hydrogen transportation along a test strip some 350 miles in length from the years 2005 to 2008. The project will also be quite challenging because of wide variations in climate and topology including very cold seasonal temperatures, not conducive to many fuel cell vehicles.<sup>15</sup>

The project is working with both governmental agencies and the private sector to produce this hydrogen corridor. The plans include the commercial feasibility of large-scale hydrogen fuel based vehicles such as cars, taxis, trucks and buses. Private vehicles will also be used in this globally anticipated study and fueling stations are to be completed so that a real-world test case can provide the evidence needed for a shift in the world's fuel dependence.

### **3.3.5. Plug-in Hybrid battery technology**

The question that challenges the plug-in investors is whether hybrid plug-ins will be successful or not. This question arises because these cars are more expensive than the conventional vehicles and hence they must provide some sort of benefit to reduce costs in the long run. One of the major factors which will determine whether this result will be observed is the battery. To better understand the factors involved with this category, a deeper look into the current battery technologies and the issues corresponding to it is necessary.

#### **3.3.5.2. Issues with battery technology**

A chief issue with PHEV battery technology is the range of travel allowed for by the batteries. PHEVs range about 40 miles per charge and the car usually takes about 4 hours to fully recharge, making this investment questionable.

Currently Nickel metal hydride batteries are being used. Like other batteries, those that use lithium work by shuttling ions (electrically charged atoms or groups of atoms) between their electrodes. When they're charging, the ions travel in one direction. When they're discharging, they go in the other. The most widely used have a positive electrode made from cobalt or manganese oxide and a negative electrode made from graphite. The electrolyte (the material through which the ions pass from one electrode to the other) is a lithium-based gel or polymer. These types of batteries are mainly used in laptops, and are not well-suited for the automotive environment, where they are subject to rapid discharging and recharging and much higher power demands and extremes of heat and cold. The problem is that the chemistry is not stable enough, so batteries suffer from overheating—and that can have an explosive effect.

## **3.4. Environmental Impact**

With so much hype about the depleting ozone layer, it is also important to analyze the environmental impact associated with the implementation of PHEVs. It will also be important to develop

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<sup>15</sup> (HydrogenCarsNow)

a better understanding of other ways in which these vehicles directly and indirectly affect the environment such as the emissions of other harmful contaminants into the atmosphere.

The major threat to the environment is the commonly known greenhouse gas, carbon dioxide (CO<sub>2</sub>). In the context of this report, CO<sub>2</sub> will be considered to be the sole greenhouse gas related to the operation and production of the PHEVs. The emissions of the gas are directly attributed to the combustion of carbon fuels (such as gasoline, natural gas, coal and other petroleum based fuels) in the following manner:

Gasoline and diesel vehicles all undergo a combustion reaction, in which carbon dioxide is produced as a byproduct along with water and heat. In this case, the actual emissions can be directly calculated (in kg) from the chemical structure of fuel and the amount consumed per year. For the situation associated with the plug-in hybrids, however, the emissions are somewhat concealed. The daily operation does not directly output any form of green house gas. Instead, it indirectly contributes to the problem when the electricity used to power the vehicle was obtained from a carbon emitting power plant.<sup>16</sup>

In Massachusetts, the top four methods for electric energy generation are natural gas, coal, nuclear and petroleum, respectively. Each means produces some form of harmful effect. For natural gas, coal and petroleum, the main pollutant is carbon dioxide, with small amounts of carbon monoxide and NO<sub>x</sub> gasses. Nuclear, unlike the other hydrocarbons, does not directly emit carbon dioxide or other chemicals typical of a combustion process. Instead, it produces hazardous nuclear waste which must be disposed of under strict safety regulations. Of the top four, nuclear is the only source that can be considered carbon neutral. Coal is the dirtiest burn (produces the most CO<sub>2</sub> per unit energy generated), followed by petroleum and the natural gas.

Strictly speaking in terms of units of energy, the large scale electricity production process more efficiently creates energy than the ICEs can. In Massachusetts, this process also produces less CO<sub>2</sub> per unit energy. It is important to note that this is true in large because of the presence of cleaner burning fuels such as natural gas as opposed to coal which is more widely used in other parts of the nation.<sup>17</sup>

Aside from the widely analyzed greenhouse gases, other common pollutants are associated with the operation of both gasoline and electric powered vehicles. Nitrogen monoxides and nitrogen dioxide, commonly abbreviated as NO<sub>x</sub> gases, are often associated with the combustion process. These pollutants are generated when nitrogen (the most abundant element in air), reacts with the oxygen in any combustion process. The reaction is unfavorable at low temperatures, which becomes a troublesome contaminant at higher temperatures. These gases, along with other volatile organic compounds (VOCs), combine to form the common phenomenon known as smog. Currently, the NO<sub>x</sub> gasses associated with ICEs are far greater than that of the electric generation processes in Massachusetts.<sup>18</sup>

These differences diminish the carbon footprint left by the transportation industry and decrease the harmful effects of VOCs associated with the daily operation of vehicles. This result is what ultimately

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<sup>16</sup> (Xie)

<sup>17</sup> (Net Generation by State by Sector)

<sup>18</sup> (Reay)

serves as the driving force behind the government incentive programs that will promote the onset of the vehicles in the future.

### **3.5. Incentives for Going Green**

Various organizations and governments offer incentives to their citizens and customers for reducing their environmental impact, in other words, for 'going green.' This section will briefly outline the various incentives offered by National Grid, EPA, the US Department of Energy, and various State Governments.

#### **3.5.1. National Grid Incentives**

For small businesses (customers with an average demand use of 200 kilowatts or less, or 40,300 kilowatt-hours or less, per month), National Grid offers a combined rebate and loan program<sup>19</sup> for the installation of energy efficient equipment. National Grid provides a free energy audit and report of recommended energy efficiency improvements. If the client decides to implement the recommended improvements, National Grid will pay 80% of the cost of the installation of energy efficient equipment. The remaining 20% can be paid off in the form of a zero interest loan over a maximum period of 24 months. Eligible energy efficient equipment includes: lighting upgrades, energy efficient time clocks, photo cells for outdoor lighting, occupancy sensors, programmable thermostats, and walk-in cooler measures.

*Energy Star* is a joint program of the US Environmental Protection Agency and the US Department of Energy that facilitates both money savings and environment protection through energy efficient products and practices. Results are already adding up – Americans, with the help of Energy Star, saved enough energy in 2007 alone to avoid greenhouse gas emissions equivalent to those from 27 million cars, all while saving \$16 billion on their utility bills. The program provides, for example, the opportunity to purchase Energy Star light bulbs and fixtures at a discounted price. These lighting products consume an average of 75% less energy and last up to 10 times longer than traditional light bulbs. The National Grid (Mass Electric) New Construction program offers incentives and technical support to help their customers who are building an Energy Star certified home. In addition, the Energy Star Rebate program offers various rebates to National Grid's residential customers for the purchase and/or installation of certain Energy Star certified equipment. Eligible equipment includes lights, washers, room air conditioners, refrigerators, central air conditioners, heat pumps, and ECM motors installed in gas furnaces, and rebates range from two dollars to three hundred dollars.

#### **3.5.2. Massachusetts Government Incentives**

**State Income Tax Credit:** Massachusetts provides an income tax credit for individuals who install renewable energy systems (solar or wind-powered) in their residences. The credit is 15% of the net expenditure (including installation) for the system, or \$1,000, whichever is less.

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<sup>19</sup> (National Grid)

**State Sales Tax Exemption:** State law exempts the user from the state sales tax for the sale of equipment directly relating to any solar, wind, or heat pump system to be used as a primary or auxiliary power system for heating or otherwise supplying the energy needs of a person's principal residence in the state.

**Corporate Income Tax Deduction:** A business which purchases a qualifying solar or wind-powered *climatic control unit* or *water heating unit* is allowed to deduct from its net income, for state tax purposes, any costs incurred from installing the unit, provided the installation is located in Massachusetts and is used exclusively in the trade or business of the corporation

### 3.5.3. Federal Incentives

The US Department of Energy has decided to provide around \$20 million<sup>20</sup> for further development of advanced batteries for PHEVs. The primary concern for developers is a reduction in battery size and weight and a simultaneous increase in the capacity and efficiency of the battery. The research fund will be utilized for achieving this goal.

Connecticut Senator Joseph Lieberman believes that 10 percent of all the new cars sold in the U.S. ought to be hybrids within two years, no matter how much they cost and states that he will introduce a bill that would make the hybrid quota the law, in part to reduce global warming. Lieberman predicts that plug-in hybrids could use alcohol-enhanced fuel to achieve up to 500 miles per gallon and contribute to the reduction in hydrocarbon pollution. By 2014, Lieberman would require 50 percent of the new cars sold in America to be hybrid electric or based on some other gasoline-saving technology. Lieberman and Senator John McCain, a Republican from Arizona, introduced a similar bill last year but it was defeated 60-38.

A tax deduction reduces the amount of income for which one is taxed. For example, if the customer's taxable income was \$50,000, a \$2,000 deduction would reduce it to \$48,000. So, the customer would pay taxes on an income of \$48,000 instead of \$50,000. This means his actual savings would be a fraction of the \$2,000 deduction. If the customer falls into the 28% tax bracket, he will save just \$560 from the \$2,000 hybrid tax deduction.

A tax credit reduces the total amount of income tax one owes. So, if a person owed \$10,000 in federal income tax, a \$2,000 credit would reduce the amount he owed to \$8,000. With a credit, his actual savings would be \$2,000.

For the 2006 tax year, hybrid vehicles, when purchased new, were allocated upwards of a \$3,150 tax credit to help offset some of the hybrid automobile expense premium. During the 2006 legislative session, the Minnesota legislature established a plug-in hybrid electric vehicle (PHEV) task force. This task force was assigned the responsibility to look into plug-in hybrid vehicles and identify barriers to their adoption and discuss strategies to overcome these barriers. The final report proposed the following incentives for owners of hybrid plug-in hybrid vehicles:

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<sup>20</sup> (US Department of Energy)

### ***Acquisition Incentives***

**Federal PHEV Tax Credit:** The federal tax credit that was directed at influencing purchase of hybrid vehicles was originally set at \$3000. That credit decreased as the demand for hybrids increased. It is currently at \$1575.

**State sales tax exemption** for PHEVs (6.5%).

### **Reduced price or free license plates**

**Fee-bates:** Develop and implement a graduated fee-based system that penalized dirty technologies and reward clean technologies. Fee-bates are tax neutral fee incentive combinations.

**Plug-in-partners type coalition:** Collecting shadow orders for PHEVs to influence production.

**“Try Before You Buy” program:** loaner or short term lease programs for potential PHEV buyers to gain experience and confidence in the technology before purchase,

**Small demo opportunity:** deploying in “HOURCAR” program for PHEVs as part of the “Try before you buy” for consumers.

**Assessment of externality value of Twin Cities air quality:** use as a guide to value of state support for avoidance.

### ***Use Incentives***

1. **Free parking** in publicly owned garages.
2. **Free battery recharging** in publicly owned garages or parking lots.
3. **Gas Taxes:** free or reduced for PHEVs.
4. **Reduced electric rates** for transportation/state purchased electricity for transportation (free to user).
5. **Free access to commuter lanes**
6. **Fee for access** to non-attainment or congested urban areas. This fee is waived for PHEVs: The fee for access concept is used in London. Transponder technology could be used to track trips and record access.
7. **Require University of Minnesota vehicles** and other state university vehicles (on campus) to be renewably powered.
8. **Lottery for a PHEV give-away:** to attract attention and provide publicity.

9. **Create a special designation** for clean transportation and **recognize communities** for public service fleets that meet criteria; could be modeled after the ENERGY STAR rating for appliances.

10. **Insurance pool**: develop and finance an insurance pool that would reduce or offer free insurance rates for PHEVs.

11. **Free public transit** for owners of PHEV.

12. **Packaging a number of incentives together** to create enough value to buy down PHEV payback time.

## 4. A System Dynamics Model of PHEVs Growth

### 4.1. Reference Modes

It is necessary to establish a set of reference modes before beginning any modeling of the system under study. The reference modes define expected behavior of the major variable in the system. In the model, one such variable is the growth of PHEVs, which can be matched to the reference modes of 'No growth', 'Overshoot and Collapse' and 'Sustainability.' The latter is obviously the most ideal reference mode that should be established by the model. The next section will briefly discuss each of the three reference modes and how they occur.

#### 4.1.1. No growth

This reference mode is witnessed when the model demonstrates little or no growth in the major variable of the system under study, namely PHEVs. This type of behavior is clearly undesirable because it would imply that the policies implemented in the model are not effective. In this case, another set of policies will have to be introduced into the model to account for the lack of growth.

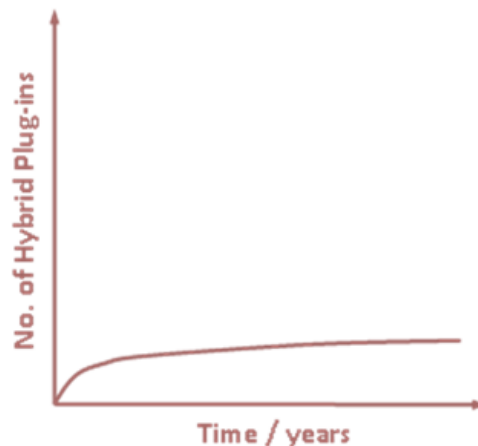


Figure 4-1 Curve shape for no growth reference mode

There are several possible scenarios that produce this behavior. Firstly, if the appeal for PHEVs does not increase, there will not be a significant number of manufacturers and potential buyers of PHEVs within the observed system. Consequently, the number of PHEVs on the road will not take off. Secondly, if the government and National Grid do not offer incentives to potential buyers of PHEVs, the cost of the vehicles will not decrease. As a result, they will have a lower appeal and the number of PHEVs on the road will not increase.

These are just a few examples of what possible situations might foster little or no growth of PHEVs. A detailed study of each factor will follow in the section 4.3, *Feedback Loops*.



### 4.1.2. Overshoot and collapse

The potential for an overshoot is another reference mode that may occur during the simulation of the model. It is produced when the major variable (PHEVs) grows very rapidly; reaches a peak, and then collapses. This type of behavior occurs when several strong causal loops influence the change in PHEVs, and one of them (resulting in a decline in PHEVs) becomes dominant over the others after some period of time.<sup>21</sup>

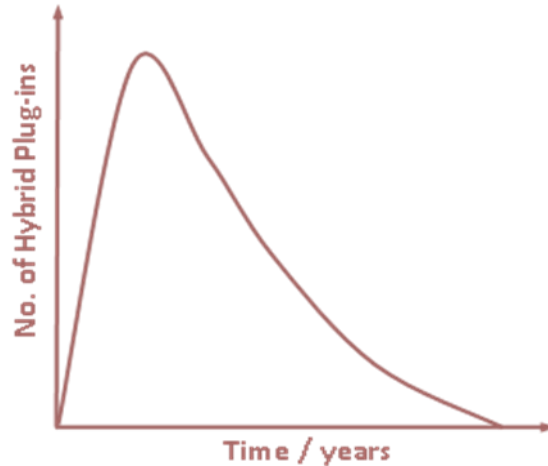


Figure 4-2 Curve shape for Overshoot and Collapse reference mode

For example, the appeal for PHEVs may increase their growth significantly. If adequate measures and policies are not implemented by National Grid in advance, the demand of electricity may exceed its maximum supply capabilities on the distribution side, as a result of which National Grid will have to increase their electricity tariffs. This will eventually increase the cost of operating and maintaining PHEVs which decreases their appeal and thus the number of PHEVs on the road.

### 4.1.3. S - Shaped growth

The third and final reference mode is the most desirable behavior, since it shows that the major system variable (PHEVs) will increase in an s-shaped curve. This implies that the number of PHEVs over a period of time shall be influenced by a number of factors and causal loop<sup>22</sup> relationships. The dominance of some of these factors over others results in s-shaped growth.

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<sup>21</sup> Causal loops may be termed 'strong' or 'weak', depending on the extent of influence they have on the major system variable, which is hybrids on the road in this case

<sup>22</sup> For more information on causal/feedback loops, please see Section 2.4.

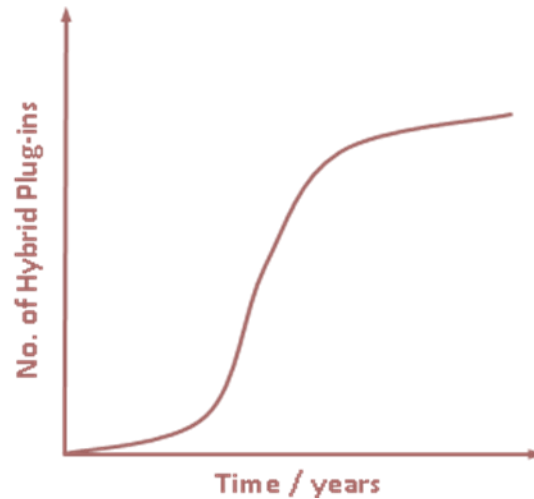


Figure 4-3 S-Shaped growth curve

An initial exponential increase in the PHEV appeal, for example, will result in a similar increase in the number of PHEVs. When the number of PHEVs on the road reaches a certain point, the *growth in* appeal of PHEVs will decrease, so that it attains a final steady value. This is because a greater number of PHEVs on the road shall imply greater electric demand and consequently higher operational costs for PHEVs. As the hybrid appeal reaches a steady value, PHEVs on the road will follow similar behavior.

S-Shaped growth is used for sustainability in several applications, including the world population growth model. The initial exponential shape and final attainment of a steady value (due to limits to growth) is a very desirable reference mode that the model will attempt to reproduce.

#### 4.2. 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 PHEVs on the road. (Please see next page for dynamic hypothesis. Various feedback loops have been explained in the next section)

# Dynamic Hypothesis

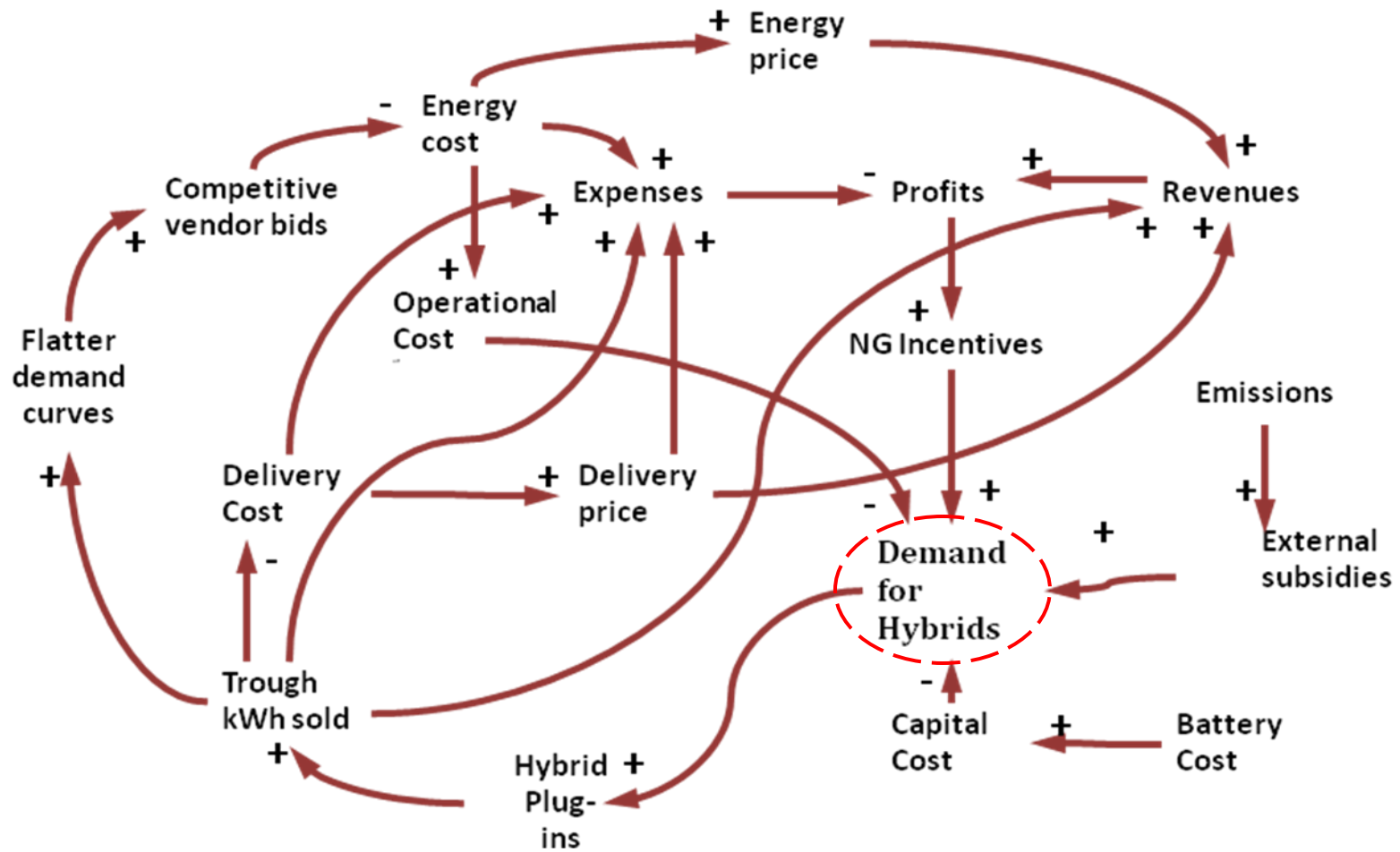


Figure 4-4 Dynamic Hypothesis

### **4.3. Feedback Loops**

The major variable that drives the model is the demand for hybrids. Therefore, the explanations of the feedback loops that follow will assume a change, particularly an increase, in the demand for hybrids. This will allow for an understanding of whether the feedback loop is either positive or negative. If a change in Demand for Hybrids 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 Demand for Hybrids it is a negative feedback loop. This report will investigate each of the pathways starting from and leading back to the demand for Hybrids and classify them as either positive or negative feedback based on the abovementioned criterion.

#### **4.3.1. Loop 1**

As the Demand for Hybrids increases, the number of PHEVs will increase. The increase in PHEVs causes an increase in Trough kWh sold since more PHEV battery charging will occur during trough periods. This increase in Trough kWh sold will cause a decrease in Delivery Cost for National Grid because more electricity is sold in bulk. Lower Delivery Cost means a reduction in Expenses which in turn causes an increase in Profits. An increase in Profits will allow National Grid to afford giving out incentives to customers who are buying PHEVs since they will sell even more electricity. Finally, if there are more incentives for customers to purchase PHEVs there will be an increase in Demand for PHEVs, thus, it is a positive feedback loop.

#### **4.3.2. Loop 2**

As the Demand for Hybrids increases, the number of PHEVs will increase. The increase in PHEVs causes an increase in Trough kWh sold since more PHEV battery charging will occur during trough periods. This increase in Trough kWh sold will cause a decrease in Delivery Cost for National Grid because, once again, more electricity is sold in bulk. A lower delivery cost to National Grid would mean a lower delivery price to the customers as well. Customers will then be using more electricity and revenues will increase. This would in turn mean an increase in profits and consequently, an increase in National Grid Incentives as well. Finally, an increase in incentives for PHEVs will mean the demand for PHEVs will increase; hence, it is a positive feedback loop.

#### **4.3.3. Loop 3**

In the third loop, as the demand for PHEVs increase, there will be an increase in the number of PHEVs on the road. This will allow National Grid to sell more electricity for charging and therefore there will be more Trough kWh sold from their daily load profiles. The more trough kWh sold, the flatter this daily load profile is. When there is a flatter demand profile, electricity generators will provide National Grid with competitive prices since they see a constant stable demand from their load profiles. A more competitive vendor bid means a lower energy cost to National Grid and therefore, they can make more profit. Again, this increase in profit will allow them to have more incentives for customers to purchase PHEVs. Again, the demand for PHEVs will increase and hence, it is a positive feedback loop.

#### 4.3.4. Loop 4

The mechanism in loop 3 will also cause a reduction in energy cost for National Grid. A lower energy cost means a lower operating cost of PHEVs to the customer, since electricity for charging is being bought for cheaper. A lower operational cost thus causes an increase in the demand for PHEVs, and so it is a positive feedback loop.

#### 4.3.5. Loop 5

As the demand for PHEVs increase, this will lead to more PHEVs on the road and more kWh electricity sold by National Grid. This will equate to an increase in revenues for National Grid as more electricity is sold. More revenues will mean more profits, and more profits will allow National Grid to give out more incentives for purchasing PHEVs. This will finally cause the demand for PHEVs to increase and thus, this is a positive feedback loop as well.

### 4.4. Model

The model for this system incorporates several sectors, reflecting the different parts of this project. The model includes the following sectors: Hybrids, National Grid Finances, Electric Distribution, PHEV batter, Appeal for Hybrids and Transformer Life. Each of these sectors models a specific aspect of the problem. When interlinking all sectors together and running them as one large unit, the final result is the system dynamics model.

#### 4.4.1. Hybrid Sector

The Hybrid sector of the model includes all factors that will affect the population of PHEV cars on the road from production to scraping and the number of current ICE cars in Massachusetts. The stocks for this sector are *Hybrids on the Road* and *New Hybrids and Gas Cars*. The flows are *Hybrid Production*, *Sales of Hybrids*, *Hybrids Scrapped*, *Gas Car Sales* and *Gas Cars Scrapped*.

**Hybrids on the Road:** This stock represents the number of PHEVs on the road. It is increased by the flow *Sales of Hybrids* and decreased by *Hybrids Scrapped*. *Sales of Hybrids* are the number of new PHEVs that are sold by car dealers and *Hybrids Scrapped* represent the number of hybrids that are lost due to accidents and other causes that force the car to be a complete loss. To increase this stock to a sustainable number was key to this model's success. Finding the correct number of these cars would allow the system to bring more profit in, reduce gas cars and help reduce emissions.

**New Hybrids:** This stock represents the number of PHEVs that are sitting in the dealers' lots. They are new cars that are waiting to be sold. The inflow is the number of PHEVs that are produced by the manufacturer, *Hybrid Production*. The out flow is *Sale of Hybrids*, the number of PHEVs sold by dealers that are taken by the consumer.

**Gas Cars:** This stock represents the number of traditional gas cars that are on the road. It is increased by the number of cars bought, *Gas Car Sales*. It is then decreases by the number of gas cars that are lost, *Gas Car Scrapped*, due to accidents and other reasons amounting to a total loss of the car. The goal is to reduce this as much as possible.

**Hybrid Production:** This is a flow that represents the addition of PHEV's into the market by manufacturers. It is influenced by the inventory control system of dealers and the aggressiveness of automobile manufacturers for introducing new PHEV's into the market.

**Sales of Hybrids:** This is an important flow into PHEV's on the road which drives the growth of PHEV's as a major system variable in the model. Similar to Hybrid Production, it is influenced by the policies of automobile dealers, as these drive the sales of PHEV's and their eventual introduction to the consumers.

**Hybrids Scrapped:** This is an outflow from PHEV's on the road which ensures that all hybrids which get depreciated to their scrap value do not remain in the system.

**Gas Car Sales:** This is an inflow into the stock of Gas Cars which is directly influenced by the number of hybrids produced. All demand for cars that has not been met by hybrid production is met by the sale of Gas Cars.

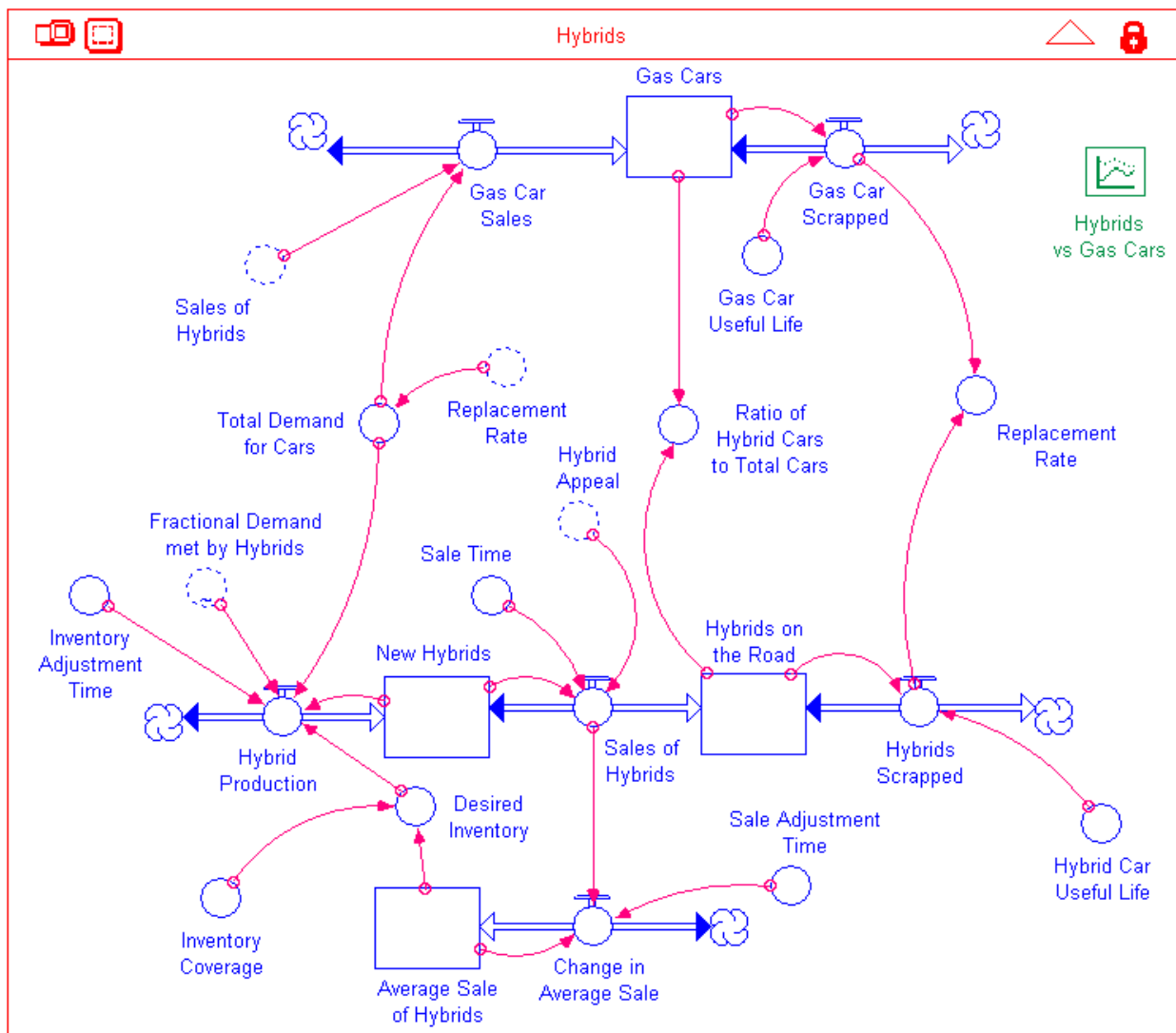


Figure 4-5 Hybrids Sector

**Gas Car Scrapped:** Similar to Hybrids Scrapped, this ensures that all gas cars reaching their scrap value are removed from the system.

**Replacement Rate:** Since the total number of cars in the system has been assumed to be constant, the all cars scrapped have to be eventually replaced. Replacement Rate is simply a parameter ensuring that replacement of cars takes place every year.

**Total Demand for Cars:** This is a parameter that ensures that the need for replacement of cars translates into their demand with a delay.

**Ratio of Hybrid Cars to Total Cars:** As its name suggests, this parameter evaluates the percentage of total cars that are hybrids. It is an important parameter since it drives the appeal for hybrids.

**Hybrid Car Useful Life:** This is the maximum life of a PHEV after which it becomes dysfunctional and may need a major overhauling.

**Gas Car Useful Life:** Similar to the previous parameter, this defines the life of a traditional car.

**Sale Time:** This parameter defines the average time taken for automobile dealers to make a successful sale of PHEV's.

**Fractional Demand met by Hybrids:** This parameter defines the fractional demand of cars that will be met by hybrids in the model. It is an important parameter as it represents the aggressiveness of manufacturers for introducing new PHEV's in the market and also drives the eventual growth of PHEV's in the system.

**Inventory Adjustment Time:** This parameter outlines the time taken by dealers for adjusting their inventory to the desired level.

**Desired Inventory:** This is the average inventory of PHEV's that dealers aim to achieve.

**Inventory Coverage:** This is parameter that determines the fraction of the desired inventory that shall be met by the PHEV dealers. It shows the aggressiveness of the dealers for having an efficient inventory control of their business.

### **Stock-flow structure of Hybrid Cars**

1.  $New\_Hybrids(t) = New\_Hybrids(t - dt) + (Hybrid\_Production - Sales\_of\_Hybrids) * dt$
2.  $INIT\ New\_Hybrids = 0$

#### **INFLOWS:**

3.  $Hybrid\_Production = Total\_Demand\_for\_Cars * Fractional\_Demand\_met\_by\_Hybrids + (Desired\_Inventory - New\_Hybrids) / Inventory\_Adjustment\_Time$

#### **OUTFLOWS:**

4.  $Sales\_of\_Hybrids = (New\_Hybrids * (Hybrid\_Appeal)) / Sale\_Time$

5.  $\text{Hybrids\_on\_the\_Road}(t) = \text{Hybrids\_on\_the\_Road}(t - dt) + (\text{Sales\_of\_Hybrids} - \text{Hybrids\_Scrapped}) * dt$
6.  $\text{INIT Hybrids\_on\_the\_Road} = 0$

**INFLOWS:**

7.  $\text{Sales\_of\_Hybrids} = (\text{New\_Hybrids} * (\text{Hybrid\_Appeal})) / \text{Sale\_Time}$

**OUTFLOWS:**

8.  $\text{Hybrids\_Scrapped} = \text{Hybrids\_on\_the\_Road} / \text{Hybrid\_Car\_Useful\_Life}$
9.  $\text{Inventory\_Adjustment\_Time} = .5$
10.  $\text{Hybrid\_Car\_Useful\_Life} = 20$
11.  $\text{Sale\_Time} = .5$
12.  $\text{Fractional\_Demand\_met\_by\_Hybrids} = .5$

**Description**

The above equations describe the change in hybrid cars. Two stocks are included for hybrids: firstly, the stock of new hybrids that have to be sold; secondly, the stock of hybrids on the road. These are time-dependent differential equations where the value of  $t=50$  years. The initial value of both hybrids on the road and new hybrids is taken to be nil initially. Two inflows are also included: one for production of hybrids and the other for their sales.

The equation for hybrid production (equation 3) is related to the total demand for cars and the fractional demand met by hybrids. Fractional demand for hybrids is a graphical function directly related to the ratio of hybrid cars to total cars. Its value ranges from 0-1 and is a powerful parameter for growth in the model. For example, if its value is 0.5, it implies that 50% of the demand for cars shall be met by hybrids. Hybrid Production is also dependent on the inventory desired by car dealers, and this relationship has been included in the equation as 'Desired\_Inventory-New\_Hybrids)/Inventory\_Adjustment\_Time'. The overall production equation is a sum of the two relationships described above.

The equation for hybrid sales acts simultaneously as an inflow for the stock of hybrids and an outflow for the stock of new hybrids, which is why it appears twice in the equation description above (equation 4 and 7). Hybrid sales are logically dependent on the number of new hybrids available in the market and the hybrid appeal. The latter is a normalized ratio ranging from 0 to 2. The equation for hybrid sales is also inversely proportional to the time taken to sell a hybrid, since a smaller sale time produces a higher number of hybrids on the road in the same modeling time.

Equation 8 describes the outflow from hybrids on the road, and has been termed 'hybrids scrapped'. It shows how hybrids on the road will eventually depreciate until they have to be replaced. This depreciation occurs over a period of time defined by the hybrid car useful life, a parameter with a value of 20 years for the model (equation 12).



### Stock-flow structure of Gas Cars

$$13. \text{Gas\_Cars}(t) = \text{Gas\_Cars}(t - dt) + (\text{Gas\_Car\_Sales} - \text{Gas\_Car\_Scrapped}) * dt$$

$$14. \text{INIT Gas\_Cars} = 330000$$

#### INFLOWS:

$$15. \text{Gas\_Car\_Sales} = (\text{Total\_Demand\_for\_Cars} - \text{Sales\_of\_Hybrids})$$

#### OUTFLOWS:

$$16. \text{Gas\_Car\_Scrapped} = \text{Gas\_Cars} / \text{Gas\_Car\_Useful\_Life}$$

$$17. \text{Gas\_Car\_Useful\_Life} = 15$$

### Description

The above equations describe the change in the stock of gas cars. Equation 13 is a time dependent differential equation for the stock of gas cars where the value of  $t=50$  years. The initial value of gas cars is defined by equation 14, and is taken to be 330,000<sup>23</sup> since this is the current approximate number of cars in Massachusetts.

Equation 15 defines the inflow of gas cars into the model, and is equal to the difference between the total demand for cars and the hybrid sales. This implies that the leftover demand for cars required after hybrid demand has been satisfied is met by the sales of gas cars. According to equation 16, the outflow for the stock of gas cars is modeled similarly to the outflow from hybrids on the road. Thus, gas cars suffer depreciation and eventually have to be scrapped over a period of time described by 'gas car useful life'. The value of this parameter is 15 years for the model (equation 17).

### Parameters in Hybrid Sector

$$18. \text{Desired\_Inventory} = \text{SMTH1}(\text{Sales\_of\_Hybrids}, .5) * \text{Inventory\_Coverage}$$

$$19. \text{Inventory\_Coverage} = .25$$

$$20. \text{Ratio\_of\_Hybrid\_Cars\_to\_Total\_Cars} = \text{Hybrids\_on\_the\_Road} / (\text{Gas\_Cars} + \text{Hybrids\_on\_the\_Road})$$

$$21. \text{Replacement\_Rate} = \text{Gas\_Car\_Scrapped} + \text{Hybrids\_Scrapped}$$

$$22. \text{Total\_Demand\_for\_Cars} = \text{SMTH1}(\text{Replacement\_Rate}, 1)$$

### Description

The above equations are important parameters that drive the dynamic behavior of cars in the hybrid sector. Equation 18 defines the desired inventory of hybrids as an average of the sales of hybrids. This implies that car dealers would desire an inventory that is equal to the number of cars sold. This equation is also depended on the inventory coverage, which is a parameter defining the fraction of desired inventory that is achieved by the car dealers.

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<sup>23</sup> (National Automobile Developers Association)

Equation 20 is an important ratio of the number of hybrid cars to the total number of cars in the model. This ratio drives the growth of hybrids by introducing a 'diffusion effect' (word-of-mouth increase in the popularity of hybrids) into the appeal for hybrids.

The 21<sup>st</sup> equation is a fundamental assumption for the model stating that the total number of cars in Massachusetts is constant, due to which the demand for new cars will be equal to total number of cars scrapped. The 22<sup>nd</sup> equation simply takes an average of this replacement of old cars by new ones, and equates the average to the total demand for cars.

#### 4.4.2. National Grid Finances

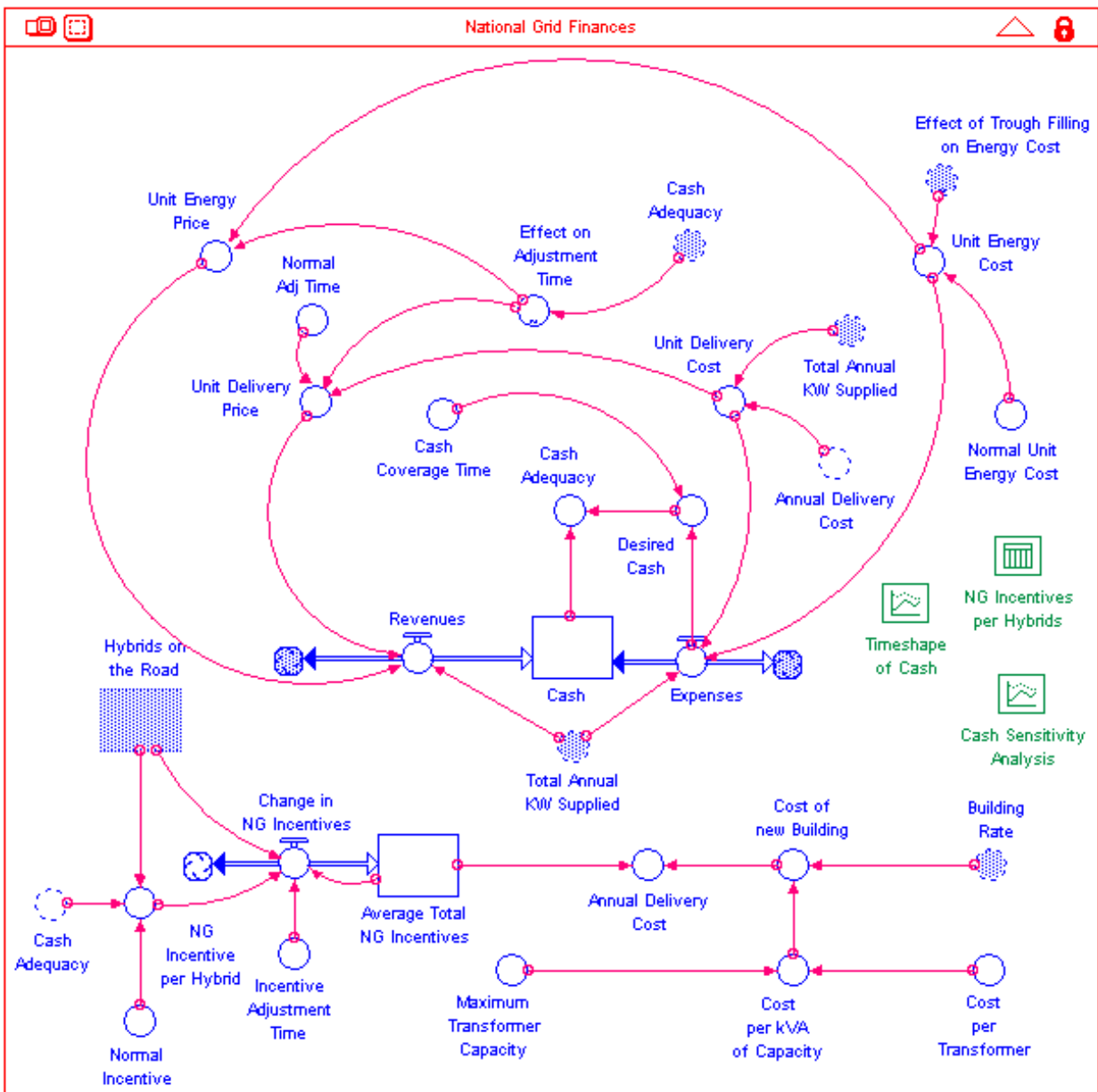


Figure 4-6 National Grid Finances Sector

The finance sector of this model reflects the anticipated revenues that National Grid will receive from their distribution of electricity. Because this project primarily concerned itself with PHEVs, it is focused on the amount electricity supplied overall and the subsequent effect from the introduction of PHEVs. Though there is a net accumulation of profit that National Grid obtains (*Cash*), they will also offer rebate incentives for PHEV owners when they purchase the car which will be a negative flow from *Cash*. This will be part of the final model as one of the policies. The stock for this model is *Cash*. The flows are *Revenue* and *Expenses*.

Cash represents the actual accumulation of profit that National Grid makes from the distribution of electricity. As a regulated industry, their overall profit should be kept constant. The inflow is Revenue and Expenses is an out flow. Initially, they are set as equivalent due to the regulated nature of the industry, which assumes that National Grid was spending as much money as they were earning. But as PHEVs are introduced, the model analyzes the increase in revenue versus the increase in expenses, thus determining a net profit.

**Normal unit energy cost:** This is the rate charged by companies generating the electricity to National Grid. In simpler terms National Grid buys electricity at an average price of 13 cents from different vendors that generate electricity.

**Unit energy cost:** This is the cost of per KWh national grid ends up paying due to the effect of trough filling. Trough filling means that National Grid is buying more electricity from vendor's which drives down the price per KWh of energy.

**Unit energy price:** This is the unit energy price charged by National Grid to the customer.

**Unit Delivery Price:** This is the delivery price charged by National Grid to its customers.

**NG Incentives:** These are incentives offered by National Grid to customers who are willing to buy and use PHEV's. They are actually modeled as a number which can be subtracted from the revenues.

**Revenues:** This is simply the revenues collected by National Grid in exchange for its services.

**Cash:** This is the amount of liquidity that National Grid possesses as a particular time. This liquidity is increased by Revenues and decreased by expenses.

**Expenses:** The expenses incurred by National Grid in supplying the electricity to its customers. Also includes the cost of electricity to National Grid and thus is a combination of both operating expenses and cost of electricity sold.

**Cash coverage time:** This is the time in which National Grid aims to collect and analyze all its revenues and expenses.

**Desired cash:** The cash that National Grid would like to acquire to cover all expenses and still remain financially healthy.

**Cash Adequacy:** A ratio between desired cash and available cash which determines the incentives National Grid will offer to its customers. A lower ratio would mean lesser incentives while a higher ratio would mean more incentives.

**Annual delivery cost:** The total annual cost incurred by National Grid in supplying the electricity from its substations to the customers.

**Unit Delivery Cost:** This is the price incurred by National Grid in delivering per unit of electricity to the consumer.

**Unit delivery price:** This is the price paid by the customer to National Grid for delivering the electricity.

**Cost per Transformer:** This is cost of one 40MVA transformer that National Grid buy and installs in its substation.

**Maximum transformer Capacity:** This is the rated load of the transformer. The transformer can handle greater loads than this but that will have an adverse effect on its life. A load under this rated load is an ideal load for the transformer.

**Cost per kVA of Capacity:** This is the cost incurred by National Grid for installing equipment to handle additional loads (kVA) of electricity.

#### **Stock-flow structure of Cash**

$$23. \text{Cash}(t) = \text{Cash}(t - dt) + (\text{Revenues} - \text{Expenses}) * dt$$

$$24. \text{INIT Cash} = \text{Desired\_Cash}$$

INFLOWS:

$$25. \text{Revenues} = \text{Total\_Annual\_KW\_Supplied} * (\text{Unit\_Delivery\_Price} + \text{Unit\_Energy\_Price})$$

OUTFLOWS:

$$26. \text{Expenses} = \text{Total\_Annual\_KW\_Supplied} * (\text{Unit\_Delivery\_Cost} + \text{Unit\_Energy\_Cost})$$

$$27. \text{Incentive\_Adjustment\_Time} = 4$$

$$28. \text{Desired\_Cash} = \text{SMTH1}(\text{Expenses}, \text{Cash\_Coverage\_Time})$$

$$29. \text{Cash\_Coverage\_Time} = 1$$

$$30. \text{Average\_Total\_NG\_Incentives}(t) = \text{Average\_Total\_NG\_Incentives}(t - dt) + (\text{Change\_in\_NG\_Incentives}) * dt$$

$$31. \text{INIT Average\_Total\_NG\_Incentives} = 0$$

INFLOWS:

$$32. \text{Change\_in\_NG\_Incentives} = (\text{Hybrids\_on\_the\_Road} * \text{NG\_Incentive\_per\_Hybrid} - \text{Average\_Total\_NG\_Incentives}) / \text{Incentive\_Adjustment\_Time}$$

33.  $NG\_Incentive\_per\_Hybrid = IF(Hybrids\_on\_the\_Road=0)THEN(0)ELSE((Cash\_Adequacy/Hybrids\_on\_the\_Road)*Normal\_Incentive)$
34.  $Normal\_Incentive = 1000000$

### Description

The above equations describe the overall behavior of cash acquired by National Grid by distributing electricity. Equation 23 is a time-dependent differential equation with  $t=50$  years. The initial value of cash defined in equation 24 equals the desired cash (since National Grid is a regulated industry with zero economic profit). According to equation 28, this is an average of the net expenses of National Grid over a period of time defined by 'cash coverage time'. The value of this parameter is 1 year, as shown in equation 29. The term 'cash' rather than 'profit' has been used since the model is dealing with a stock and cash is the accumulation of profits over a long period of time in the model.

The inflow for cash (revenue) is outlined in equation 25. Revenue for National Grid simply equals the net income received from the supply of electricity.

National Grid Incentives are possible discounts that it may offer to potential buyers of hybrids. Since these incentives change dynamically in the model, an average of their value over a period of time has been taken. This period of time is defined in the model as incentive adjustment time (equation 27).

Moreover, the discounts offered by National Grid are decided by analyzing the ratio of cash adequacy to the number of hybrids on the road. The value of cash adequacy ranges from 0 to 1, and since the mentioned ratio is  $Cash\ Adequacy / Number\ of\ Hybrids$ , its value also ranges between 0 and 1. A higher value of National Grid Incentives per Hybrid implicitly states that National Grid would be more willing to offer incentives since it has sufficient cash to cover its expenses and the number of hybrids on the road will not be appreciable. In such a state, it would logically be more inclined towards offering incentives to potential customers for buying hybrids. The maximum amount of discount National Grid would normally offer is assumed to be \$1 million (in total for all hybrids – equation 34). Hence National Grid Incentives per hybrid are defined by equation 33 as the product of the ratio of cash adequacy to number of hybrids and the normal incentive.

The outflow for cash (expenses) is outlined in equation 26. Similar to revenue, expenses for National Grid simply equal the net expense incurred for providing electricity supply and distribution.

### National Grid as a Regulated Industry

35.  $Cash\_Adequacy = Cash/Desired\_Cash$
36.  $Annual\_Delivery\_Cost = 30000+Cost\_of\_new\_Building+Average\_Total\_NG\_Incentives$
37.  $Unit\_Delivery\_Cost = Annual\_Delivery\_Cost/SMTH1(Total\_Annual\_KW\_Supplied,STOPTIME)$
38.  $Normal\_Adj\_Time = 1$
39.  $Unit\_Delivery\_Price = SMTH3(Unit\_Delivery\_Cost,Effect\_on\_Adjustment\_Time*Normal\_Adj\_Time)$
40.  $Unit\_Energy\_Price = SMTH1(Unit\_Energy\_Cost,Normal\_Adj\_Time*Effect\_on\_Adjustment\_Time)$
41.  $Unit\_Energy\_Cost = Normal\_Unit\_Energy\_Cost*Effect\_of\_Trough\_Filling\_on\_Energy\_Cost$

42. Normal\_Unit\_Energy\_Cost = .13
43. Effect\_on\_Adjustment\_Time = GRAPH(Cash\_Adequacy)  
 (0.00, 3.96), (0.2, 3.08), (0.4, 2.52), (0.6, 1.92), (0.8, 1.44), (1.00, 1.00), (1.20, 0.74), (1.40, 0.54),  
 (1.60, 0.44), (1.80, 0.42), (2.00, 0.38)

**Description**

Since National Grid is a regulated industry, it has to maintain a minimal markup between the unit electricity cost and price. The unit electricity cost can be further broken down into delivery cost and energy cost. Delivery cost is the expense incurred by National Grid for distributing electricity to various consumers, whereas the energy cost is a fixed rate at which National Grid buys electricity from its suppliers to provide it to the end-user. Similarly, delivery and energy price are the amounts billed to customers for electricity used by them. The fact that National grid is a regulated industry implies that federal decision makers study the net profit acquired by National Grid and make decisions on raising or lowering the energy/delivery price accordingly.

The unit energy cost according to equation 41 is the product of the normal unit energy cost (0.13) and the effect of trough filling on energy cost. The latter is a graphical function that describes how a utilization of surplus electricity capacity at low demand times translates into a reduced energy cost. This is because at low demand times nuclear and hydro power plants generate electricity. These plants have significantly lower maintenance costs than peak demand oil and coal fired power plants.

The unit energy price is an average of the unit energy cost over a period of time described by the product of the normal adjustment time and the effect on adjustment time in the model. This is another graphical function dependent on cash adequacy (mentioned previously in the same section). The graphical function is defined by equation 43, and implies that federal decision makers catch up with National Grid more quickly when it has a surplus of cash over expenses (Cash Adequacy >1), and lag behind in making sure National Grid has zero economic profit when it has less cash than expenses (Cash Adequacy <1)

Unit delivery cost is described in equation 37 as the ratio of the total annual cost of supplying electricity to the total electricity supplied annually. An average of the annual electricity supplied has been taken over the modeling time, to make the effect on cost less erratic (resistant to sudden/short changes in total electricity supplied). The value of this ratio is expected to range between 0 and 15 cents. The annual delivery cost is assumed to be the sum of \$30,000 (average expected delivery cost), the cost of additional capacity upgrades, and the average incentives offered by National Grid. This is evident from equation 36. Similar to unit energy price, the unit delivery price is an average of the unit delivery cost over the period of time defined by the product of the normal adjustment time and the effect on adjustment time, as observable in equation 40.



**4.4.3. Electricity Distribution**

This sector looked at the power delivery ability of National Grid. Like *Hybrid Appeal*, this sector has no stock or flows, only key converters. Using data that was gathered about the daily demand placed

on National Grid, this sector was built to reflect how electricity is demanded then supplied. It took several important characteristics of the demand into consideration including the demand curve and how the demand for electricity varies over an entire day. The next major part to this sector is the effect that the hybrids have on the demand. PHEVs need to be plugged-in to recharge, so this model looked at how the charging of the vehicles would affect the overall daily demand curves.

**Daily Hybrid Demand:** This variable gives a value to the KW demand for all the hybrid cars on the road. It is determined by multiplying the average KW used per hybrid with the number of hybrids on the road.

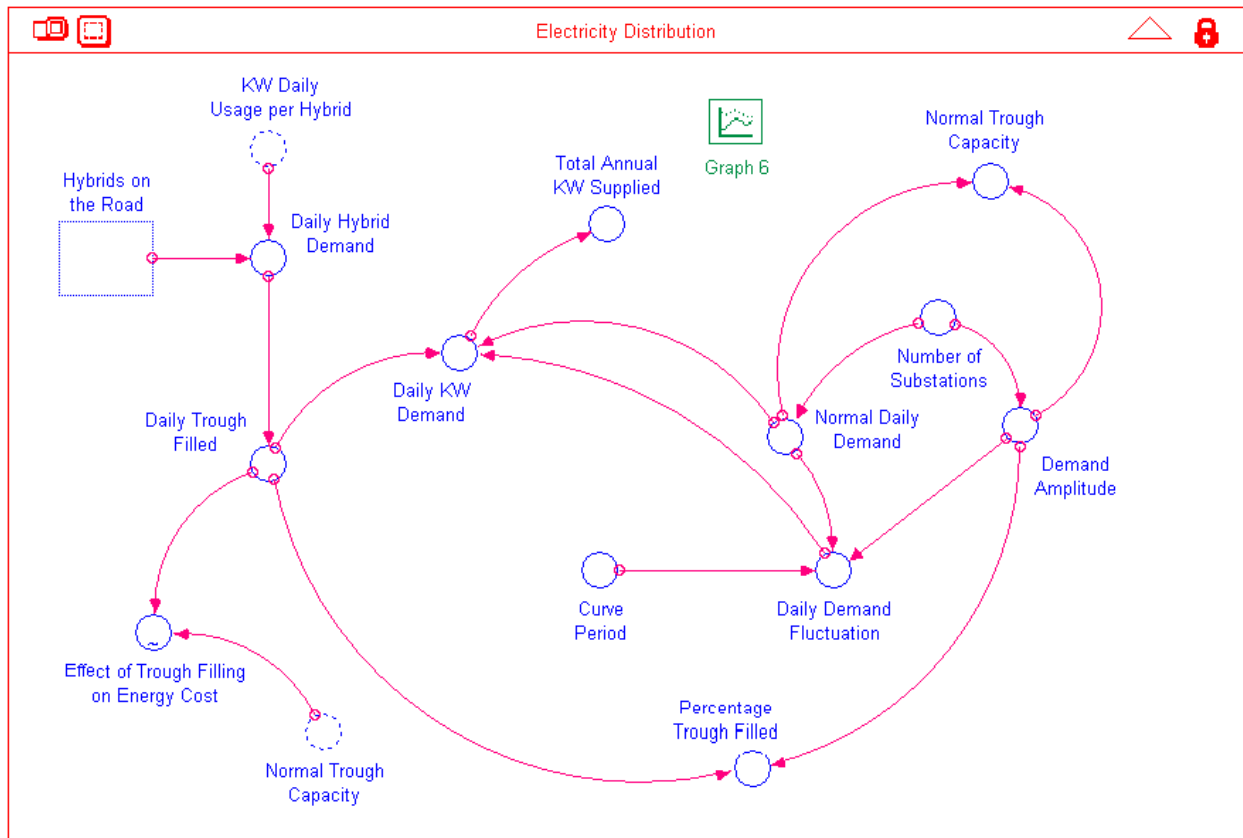


Figure 4-7 Electricity Distribution Sector

**Daily Trough Filled:** Here, the total kW demanded by hybrids is converted into MVA. This is done by dividing the above variable by 0.8 (the power factor). Since the demand curves are in MVA, this step is essential in order to determine the change in the daily curves.

**Effect of Trough Filling on Energy Cost:** This is a graphical function between 0.5 and 1 and is inversely proportional to the above mention Daily Trough Filled. As the trough gets filled more and more, the cost of energy should decrease since National Grid is making more money and hence is required to reduce costs in order to maintain a regulated industry.

**Daily KW Demand:** This variable adds the extra demand coming from hybrids to the normal daily curve in order to determine the new daily load with hybrids on the hybrid. It is set up in such a way so that the demand for hybrids only adds to the troughs.

**Total Annual KW Supplied:** A smooth function of the Daily KW Demand taken over a period of 1 yr in order to obtain a macro view of how the coming of hybrid cars is affecting the load profiles.

**Curve Period:** A numerical value of 1/365 since the load curve is daily but the model is running in years. Thus a frequency of 1/365 for the curves makes them occur once a day.

**Demand Amplitude:** This parameter is used to define the peaks and troughs of the load curve. The load curve, which behaves like a sinusoidal wave, experiences a fluctuation of 20 MVA. This creates a maximum load of 60MVA and minimum load of 20MVA per substation. Multiplying it by the number of substations in Massachusetts gives total demand curve for Massachusetts.

**Normal Daily Demand:** Gives the centered level of the load curve. Each substation experiences a centered level of 40 MVA every day. Multiplying that by the Number of Substations in Massachusetts gives the centered level of the demand curve of Massachusetts, which is known as the Normal Daily Demand.

**Normal Trough Capacity:** This variable is used to define the space available in the trough of the demand curve which can be filled by the additional load of hybrids. It is calculated by subtracting the demand amplitude from the normal daily demand.

**Number of Substations:** Defines the total number of Substations in Massachusetts, which was found to be 500; based on the findings of previous project teams.

**Daily Demand Fluctuation:** This function creates a sinusoidal load curve centered on a level of 40MVA and having peaks and troughs of 60MVA and 20MVA. It is given by subtracting the cosine wave of amplitude 20MVA from the Normal Daily Demand, which is the centered average value.

**Percentage Trough Filled:** This gives a measure of the amount of trough that is filled by the additional load of PHEV's. It is given by dividing the Daily Trough Filled by the Demand Amplitude and multiplying the result by 100 to give a percentage. Through this parameter, the amount of trough left to be filled can be determined.

#### **Parametric Equations for Electricity Distribution**

44.  $Curve\_Period = 1/365$

45.  $Daily\_Demand\_Fluctuation = Normal\_Daily\_Demand - COSWAVE(Demand\_Amplitude, Curve\_Period)$

46.  $Daily\_Hybrid\_Demand = Hybrids\_on\_the\_Road * KW\_Daily\_Usage\_per\_Hybrid$

47.  $Daily\_KW\_Demand =$

$(IF(Daily\_Demand\_Fluctuation < Normal\_Daily\_Demand) THEN (Daily\_Trough\_Filled + Daily\_Demand\_Fluctuation) ELSE (Daily\_Demand\_Fluctuation))$

48.  $Daily\_Trough\_Filled = Daily\_Hybrid\_Demand / 0.8$

49.  $Demand\_Amplitude = 20000 * Number\_of\_Substations$



50.  $\text{Normal\_Daily\_Demand} = 40000 * \text{Number\_of\_Substations}$
51.  $\text{Normal\_Trough\_Capacity} = \text{Normal\_Daily\_Demand} - \text{Demand\_Amplitude}$
52.  $\text{Number\_of\_Substations} = 500$
53.  $\text{Percentage\_Trough\_Filled} = \text{Daily\_Trough\_Filled} / \text{Demand\_Amplitude} * 100$
54.  $\text{Total\_Annual\_KW\_Supplied} = \text{SMTH3}(\text{Daily\_KW\_Demand} * 365, 1)$
55.  $\text{Effect\_of\_Trough\_Filling\_on\_Energy\_Cost} = \text{GRAPH}(\text{Daily\_Trough\_Filled} / \text{Normal\_Trough\_Capacity})$   
 (0.00, 1.00), (0.1, 0.995), (0.2, 0.99), (0.3, 0.985), (0.4, 0.95), (0.5, 0.895), (0.6, 0.79), (0.7, 0.615),  
 (0.8, 0.525), (0.9, 0.5), (1, 0.495)

## Description

The above equations describe the nature of the electricity distribution sector and the factors that affect it. The Daily Hybrid Demand (Equation 46) is the extra load that comes in to the grid systems with the coming of hybrid cars. As it can be seen, it is simply a combination of the number of Hybrids on the Road with the KW Daily Usage per Hybrid. This is then converted to MVA in Equation 48 in order to keep it consistent with the daily load curve characteristics. As more and more of this trough gets filled the cost of energy should go down (Equation 55). It describes an inversely proportional relationship in order to indicate that as National Grid makes more money when the trough rises, they are expected to reduce costs in order to maintain a regulated industry.

The Normal Daily Demand gives an average base value of the KW used in all the substations in MA (Equation 50). This is done by multiplying the average load on the substations (20000kW) with the number of substations (Equation 52). Along with this base load, it is assumed that a cosine wave is acting on the substations. The amplitude of this wave is given by Equation 44 so that it occurs once a year and its amplitude is given by Equation 49; this multiplies the fluctuation amplitude of 20000kW with the number of substations.

Finally, the extra capacity coming from hybrid cars is added to the overall daily load already present. This is done in Equation 47 which is set up in such a way so that the extra demand on the distribution sector from hybrid cars only adds to the trough and not to the peaks.

### 4.4.4. Trough Filling

This sector models the policy and decisions taken by National Grid for upgrading their substations to ensure that the electricity supply matches demand. The daily trough filled increases due to the introduction of PHEV's into the system and the resultant charging that occurs due to their use. The trough can be visualized as a reservoir of surplus capacity that can be filled by the charging of PHEV's without incurring excess additional expenses for National Grid. The trough in daily demand variation represents a time when there is low electric demand which is met by nuclear and hydro-powered generators. These generators have lower maintenance costs and times, and are hence preferred by National Grid over coal and oil fired power stations that are used during peak demand times. As the trough fills up, the life of the equipment used by National Grid for electricity distribution (transformers and substations) decreases. This sector therefore models the policies implemented by National Grid for maintaining a nominal trough capacity. A detailed description of the dynamics occurring in this model is presented below.

**Trough Capacity:** This is a stock representing the capacity of troughs created due the daily variation of electric demand. A change in the trough capacity implies a change in the number of PHEV's that can be charged during times of low electric demand. This is because one of the policies in the model is that the

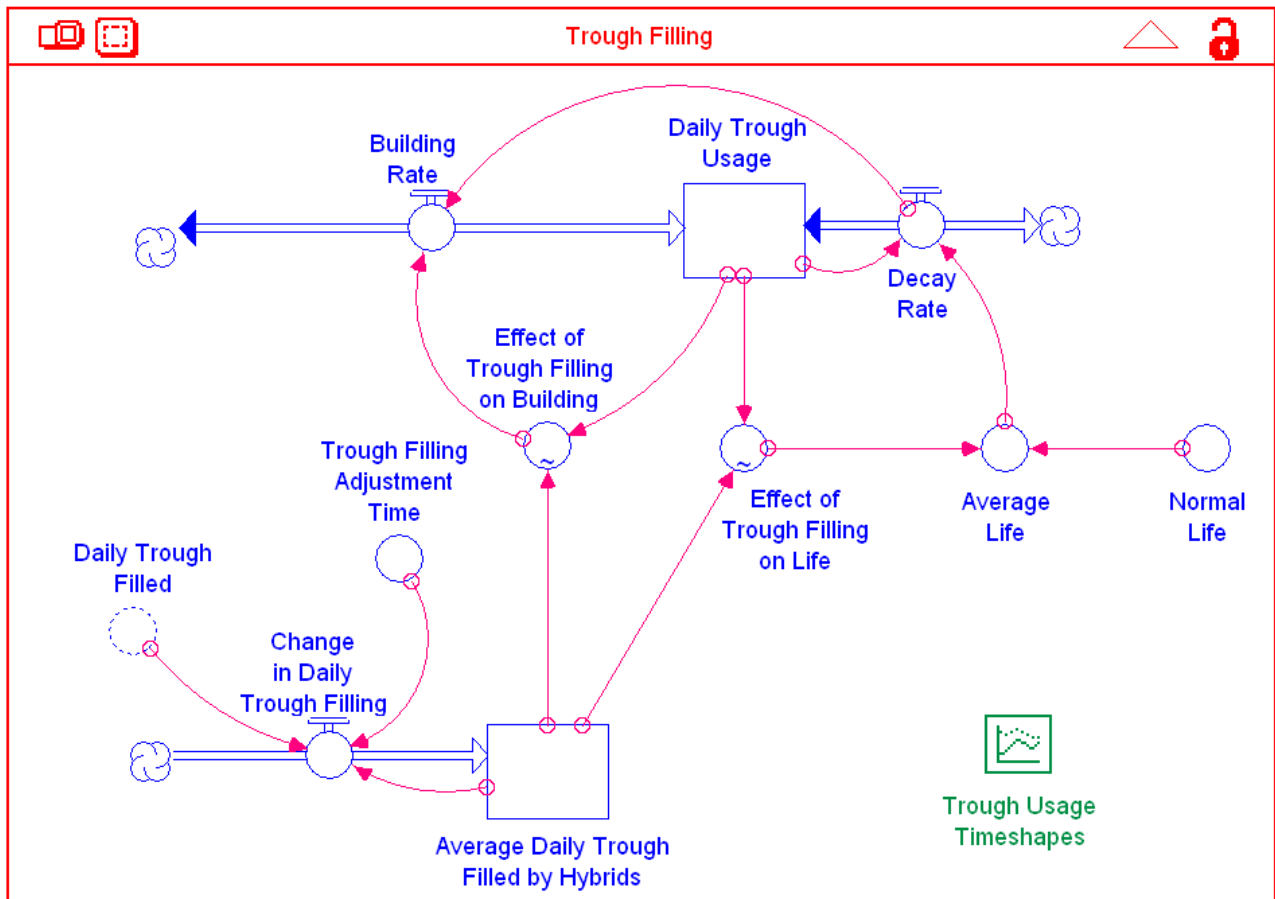


Figure 4-8 Stock flow structure for Trough Capacity

charging of PHEV's occurs only during trough periods to reduce the overall load/demand of electricity on the local grid.

**Decay Rate:** This is an outflow that determines the decrease in trough capacity due to the usage and consequent charging of PHEV's during trough time-periods.

**Building Rate:** This is an inflow that is directly related to the decay rate, since National Grid is expected to make decisions and counter-measures to maintain a nominal trough capacity as the decay rate increases.

**Normal Life:** This is a parameter defining the normal life of a transformer/substation

**Average Life:** This is a parameter that determines the actual life of a transformer/substation based on the an increase in electric demand during trough time-periods due to the charging of PHEV's

**Effect of Trough Filling on Life:** This is a graphical function that relates the amount of trough filled to the life of a transformer/substation. For more information, please see the description of the equations that follow.

**Effect of Trough Filling on Building:** Similar to the previous graphical function, this parameter relates the amount of trough filled daily to the building rate for upgrading trough capacity. For more information on this function, please see the description of the equations that follow.

### Stock-flow structure of Trough Capacity

56.  $Trough\_Capacity(t) = Trough\_Capacity(t - dt) + (Building\_Rate - Decay\_Rate) * dt$

57.  $INIT\ Trough\_Capacity = Demand\_Amplitude$

OUTFLOWS:

58.  $Building\_Rate = SMTH1(Decay\_Rate,1)*Effect\_of\_Trough\_Filling\_on\_Building$

INFLOWS:

59.  $Decay\_Rate = Trough\_Capacity/Average\_Life$

60.  $Average\_Life = Normal\_Life*Effect\_of\_Trough\_Filling\_on\_Life$

61.  $Normal\_Life = 170$

62.  $Effect\_of\_Trough\_Filling\_on\_Life = GRAPH(Daily\_Trough\_Filled/Trough\_Capacity)$   
 (0.00, 1.56), (0.273, 1.47), (0.545, 1.34), (0.818, 1.17), (1.09, 0.98), (1.36, 0.81), (1.64, 0.59), (1.91, 0.39), (2.18, 0.22), (2.45, 0.12), (2.73, 0.07), (3.00, 0.06)

63.  $Effect\_of\_Trough\_Filling\_on\_Building = GRAPH(Daily\_Trough\_Filled/Trough\_Capacity)$   
 (0.00, 0.015), (0.2, 0.13), (0.4, 0.22), (0.6, 0.383), (0.8, 0.607), (1.00, 1.00), (1.20, 1.38), (1.40, 1.61), (1.60, 1.79), (1.80, 1.90), (2.00, 1.98)

### Description

The above list of equations describes the behavior of daily trough usage. Equation 56 defines the change in trough usage. Since it is a stock, the equation is a time-dependent equation with the value of  $t=50$  years (equation 57). The initial value of daily trough usage is equal to the amplitude of the daily demand curve. This is a sinusoidal function representing the typical variation of demand during a day. For the model, the amplitude is taken to be 20 MVA, which is consequently also the initial value of the daily trough usage.

Decay Rate as the inflow is defined to be related to the trough capacity. Equation 66 shows that the structure of the inflow equation in this case is similar to the depreciation of cars incorporated in the hybrid sector. As more and more trough capacity is used, the decay rate increases. Overall, the decay rate is an average of the trough capacity over a period of time defined by Average Life (of a substation). According to equation 60, this parameter is the product of the normal life of a substation operated by National Grid (170 years) and the Effect of Trough Filling on Life. Since the modeling time is merely 50 years, no significant measures take place to upgrade the trough capacity.

The Effect of Trough Filling on Life is a graphical function related to the ratio of the daily trough filled to the trough capacity. This ratio effectively defines the proportion of trough filled over the

modeling period of time (50 years). A value of 1 for this ratio implies that the effect is non-existent (i.e. the life does not change). At lower values of the ratio, the effect is positive and the life of a substation increases above the normal life (170 years). On the other hand, at higher values of this ratio the effect is negative. This implies that when excess demand for electricity (created due to the introduction of PHEV's) exceeds the trough of the daily load variation, the life of a substation decreases below the normal life.

The outflow to trough capacity is termed the building rate. According to equation 58, this is a product of an average of the decay rate over a year and the effect of trough filling on building. The latter is also a graphical function dependent on the ratio of the daily trough filled to the trough capacity. Similar to the previously mentioned graphical function, the effect is nil at the value of 1 of the ratio (no building is required). As the ratio's value increases above 1 and approaches 2, the effect is doubled. This implies that decision makers become more aggressive towards building more substations to meet the increasing demand. As the value of the ratio decreases below 1 and approaches 0, the effect decreases since building (upgrading) trough capacity is no longer important.

#### 4.4.5. Hybrid Appeal

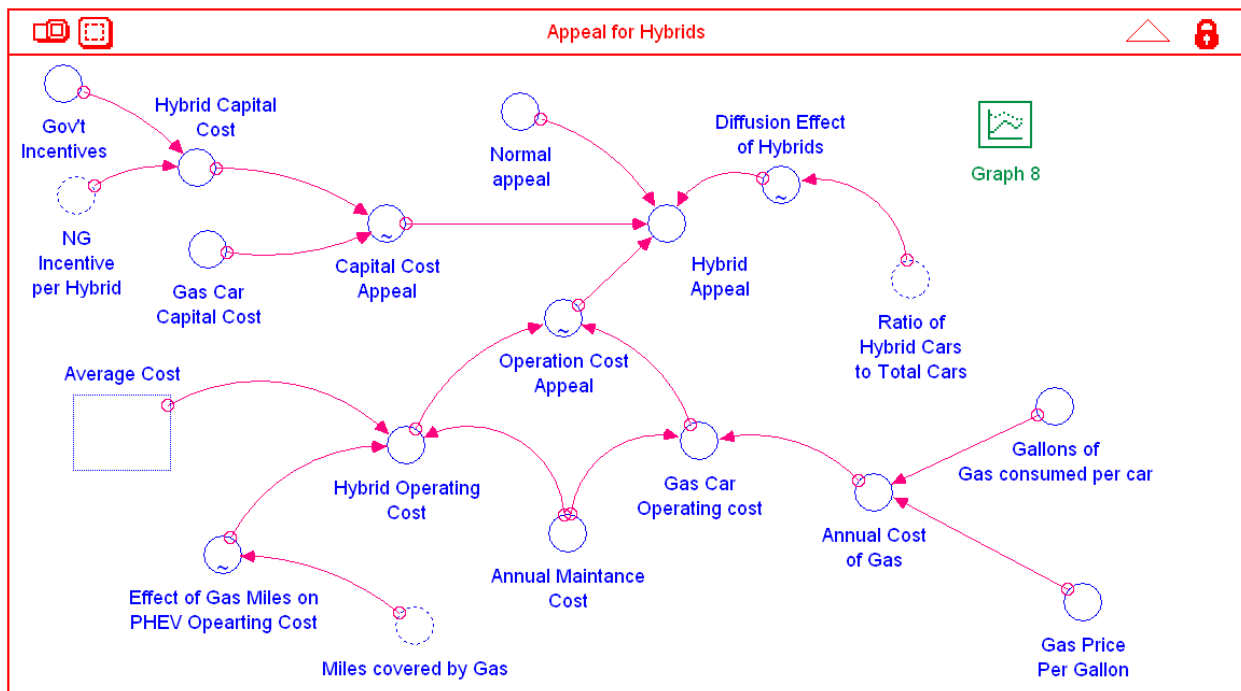


Figure 4-9 Appeal for Hybrids Sector

This sector represents the appeal of purchasing a hybrid car to the consumer. The sector is calculated by comparing the cost of a traditional gas car to a PHEV car. This is done by looking at the capital, purchase cost, of the different type of cars and the operational cost of the cars. Unlike all the other sectors, there are no stocks or flows in this sector; this sector is made up completely of converters. The two main groups are the operational cost and the capital cost. The capital cost compares the capital cost of a PHEV to that of a gas car and operational cost compares the yearly

operating cost of a PHEV to a gas car. The capital cost of the PHEVs is set at \$30,000, the projected cost for a production hybrid, and it is adjusted with a rebate from National Grid and also a rebate from the Government for buying that type of car. Operational Cost combined the cost of charging along with a constant, the amount spent on tires, wiper blades, driving lights and other services, that is added to both gas cars' and PHEV cars' operational cost.

### Equations for evaluating Appeal for Hybrids

64.  $\text{Annual\_Cost\_of\_Gas} = \text{Gallons\_of\_Gas\_consumed\_per\_car} * \text{Gas\_Price\_Per\_Gallon}$
65.  $\text{Annual\_Maintance\_Cost} = 700$
66.  $\text{Gallons\_of\_Gas\_consumed\_per\_car} = 541$
67.  $\text{Gas\_Car\_Operating\_cost} = \text{Annual\_Cost\_of\_Gas} + \text{Annual\_Maintance\_Cost}$
68.  $\text{Gas\_Car\_Capital\_Cost} = 17000$   
 $\text{Gas\_Price\_Per\_Gallon} = 3.19$
69.  $\text{Gov't\_Incentives} = 3000 - \text{STEP}(2000, 10) * 0$
70.  $\text{Hybrid\_Appeal} = \text{Capital\_Cost\_Appeal} * \text{Operation\_Cost\_Appeal} * \text{Normal\_appeal}$
71.  $\text{Hybrid\_Capital\_Cost} = 30000 - (\text{NG\_Incentive\_per\_Hybrid} + \text{Gov't\_Incentives})$
72.  $\text{Hybrid\_Operating\_Cost} = (\text{Annual\_Maintance\_Cost} + \text{Average\_Cost}) * \text{Effect\_of\_Gas\_Miles\_on\_PHEV\_Opearting\_Cost}$
73.  $\text{Normal\_appeal} = 1$
74.  $\text{Capital\_Cost\_Appeal} = \text{GRAPH}(\text{Hybrid\_Capital\_Cost} / \text{Gas\_Car\_Capital\_Cost})$
75. (0.00, 1.98), (0.5, 1.36), (1.00, 1.00), (1.50, 0.63), (2.00, 0.49), (2.50, 0.38), (3.00, 0.27), (3.50, 0.19), (4.00, 0.13), (4.50, 0.08), (5.00, 0.03)
76.  $\text{Effect\_of\_Gas\_Miles\_on\_PHEV\_Opearting\_Cost} = \text{GRAPH}(\text{Miles\_covered\_by\_Gas})$
77. (0.00, 1.00), (10.0, 1.10), (20.0, 1.20), (30.0, 1.30), (40.0, 1.40), (50.0, 1.50), (60.0, 1.60), (70.0, 1.70), (80.0, 1.80), (90.0, 1.90), (100, 2.00)
78.  $\text{Fractional\_Demand\_met\_by\_Hybrids} = \text{GRAPH}(\text{Ratio\_of\_Hybrid\_Cars\_to\_Total\_Cars})$
79. (0.00, 0.06), (0.1, 0.405), (0.2, 0.625), (0.3, 0.73), (0.4, 0.79), (0.5, 0.845), (0.6, 0.89), (0.7, 0.935), (0.8, 0.965), (0.9, 0.99), (1, 1.00)
80.  $\text{Operation\_Cost\_Appeal} = \text{GRAPH}(\text{Gas\_Car\_Operating\_cost} / \text{Hybrid\_Operating\_Cost})$
81. (0.00, 0.00), (0.5, 0.53), (1.00, 1.00), (1.50, 1.21), (2.00, 1.41), (2.50, 1.60), (3.00, 1.71), (3.50, 1.81), (4.00, 1.89), (4.50, 1.94), (5.00, 2.00)

### Description

**Annual\_Cost\_of\_Gas:** This is the yearly total of gasoline for a gas car.

**Annual\_Maintance\_Cost:** This is a predetermined yearly amount that was set to represent the cost of universal car related maintained. This cost included basic car parts, like tires and wiper blades, and general services like a car wash or the balancing of tiers. This was a constant applied to both hybrids and gas cars.

**Gallons\_of\_Gas\_consumed\_per\_car:** This was the amount of gallons that the average car will use over the course of a year. The number was found from the fact that the average distance traveled was around 10,000 miles and that the average car had a rating of miles per gallon of a little less than 20 MPG. This was used to determine Annual\_Cost\_of\_Gas.

**Gas\_Car\_Operating\_cost:** This is the total yearly amount spent on operating a gas car.

**Gas\_Car\_Capital\_Cost:** This is the cost of a new gas car, this was the mid-range of prices \$17,000.

**Gas\_Price\_Per\_Gallon:** The cost of a gallon of gas, set at \$3.19, slightly lower than the current national average of \$3.50 as of 21APRIL2008.<sup>24</sup>

**Gov't\_Incentives:** These are government incentives that will be offered to consumers who purchase a PHEV, they are set as tax breaks for the consumer, taking off at first \$3,000, then the amount gradually decreases as PHEVs become more common place.

**Hybrid\_Appeal:** This represents how appealing a PHEV is compared to a normal gas car. This is a function that takes into account a comparison of the operating cost of PHEVs and of gas cars. The ratio is then scaled between 0 and 2, to show as the price difference changes, the appeal affect changes. A higher PHEV cost results in a number closer to zero, low appeal, but a lower cost results in a higher number, higher appeal.

**Hybrid\_Capital\_Cost:** This is the price that the consumer pays for a new PHEV. The price was set at \$30,000 the MSRP of a Chevrolet Volt. The price is affected by Gov't\_Incentives and National\_Grid\_Incentives that reduce the cost.

**Hybrid\_Operating\_\_Cost:** This is the total yearly amount spent on operating a PHEV car.

**Normal\_appeal:** This is a constant that is used to normalize the Hybrid\_appeal parameter.

**Capital\_Cost\_Appeal:** This is a graphical function that compares hybrid\_capital\_cost to gas\_car\_captial\_cost. The graph works on a scale of 0 to 2. The higher the ratio the more the greater the hybrid appeal is, the lower the ratio the less.

**Diffusion\_Effect\_\_of\_Hybrids:** This is a graphical function that is used to represent a word of mouth function; as more hybrids are on the road, the more they are seen. The more hybrids results in a greater appeal and drives the hybrid\_appeal sector.

**Effect\_of\_Gas\_Miles\_on\_PHEV\_Opearting\_Cost:** This is a graphical function that is used simulates how the hybrid uses an ICE. Depending on how the car is driven, the car can be driven by either the gasoline engine or electric motor.

**Operation\_Cost\_Appeal:** This graphical function compares hybrid\_operational\_cost to gas\_car\_operational\_cost. The graph works on a scale of 0 to 2. The higher the ratio the more the greater the hybrid appeal is, the lower the ratio the less.

#### 4.4.6. PHEV Battery

This sector looks specifically at the batteries that the PHEVs use. Like the Hybrid Appeal sector, there are no stocks in this sector, only converters. The main function of this sector is to model the behavior of the battery technology and how it affects the PHEV in their appeal, their operation and their sales.

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<sup>24</sup> (Associated Press)

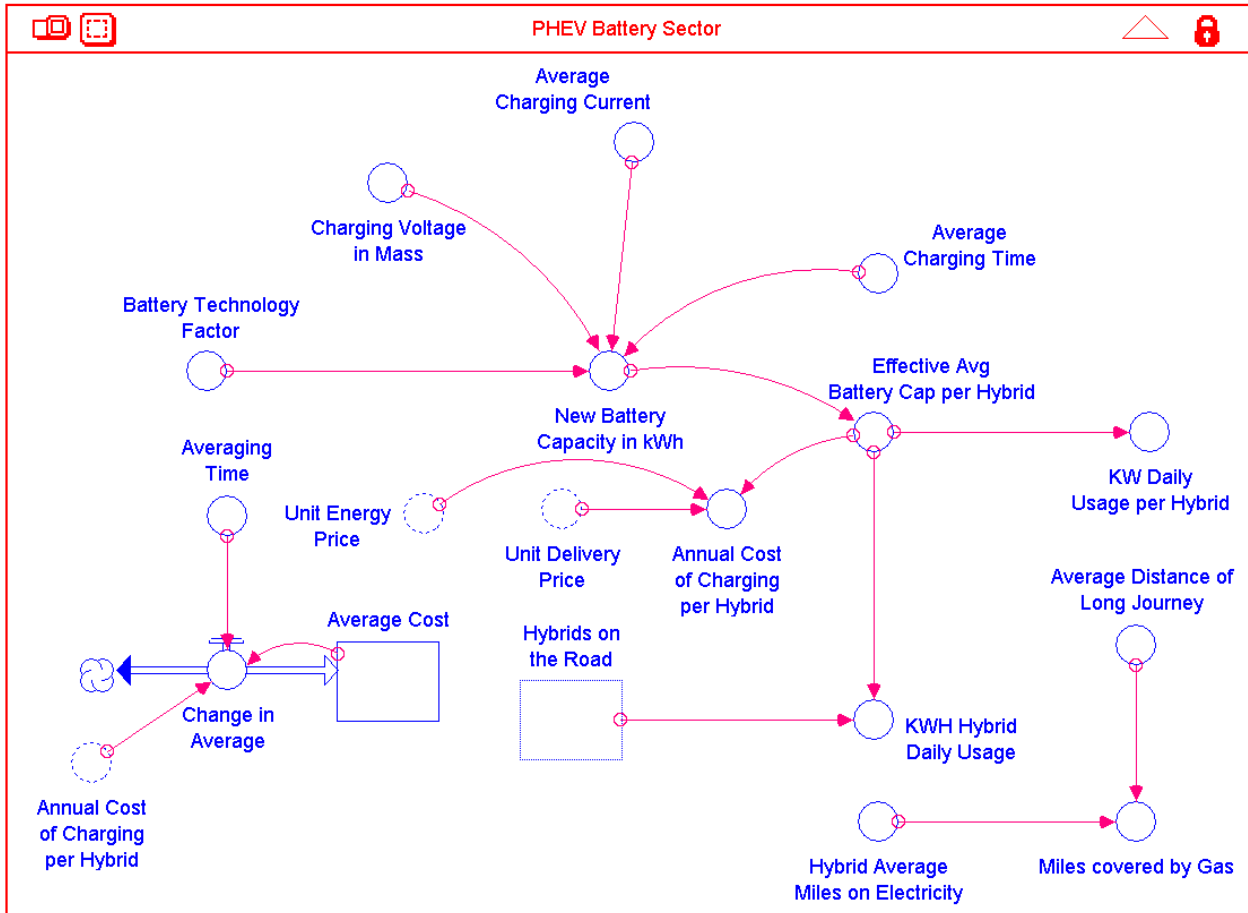


Figure 4-10 PHEV Battery Sector

82.  $Average\_Cost(t) = Average\_Cost(t - dt) + (Change\_in\_Average) * dt$

83.  $INIT\ Average\_Cost = 419$

INFLOWS:

84.  $Change\_in\_Average = (Annual\_Cost\_of\_Charging\_per\_Hybrid - Average\_Cost) / Averaging\_Time$

85.  $Annual\_Cost\_of\_Charging\_per\_Hybrid = 365 * Effective\_Avg\_Battery\_Cap\_per\_Hybrid * (Unit\_Delivery\_Price + Unit\_Energy\_Price)$

86.  $Average\_Charging\_Current = 13$

87.  $Average\_Charging\_Time = 4$

88.  $Average\_Distance\_of\_Long\_Journey = 80$

89.  $Average\_kWh\_per\_mile = .4$

90.  $Averaging\_Time = 1$

91.  $Battery\_Technology\_Factor = 1$

92.  $Charging\_Voltage\_in\_Mass = 120$

93.  $Effective\_Avg\_Battery\_Cap\_per\_Hybrid = New\_Battery\_Capacity\_in\_kWh$

94.  $\text{Hybrid\_Average\_Miles\_on\_Electricity} = \frac{\text{Effective\_Avg\_Battery\_Cap\_per\_Hybrid}}{\text{Average\_kWh\_per\_mile}}$
95.  $\text{KW\_Daily\_Usage\_per\_Hybrid} = \frac{\text{Effective\_Avg\_Battery\_Cap\_per\_Hybrid}}{\text{Average\_Charging\_Time}}$
96.  $\text{KWH\_Hybrid\_Daily\_Usage} = \text{Hybrids\_on\_the\_Road} * \text{Effective\_Avg\_Battery\_Cap\_per\_Hybrid}$
97.  $\text{Miles\_covered\_by\_Gas} = \text{Average\_Distance\_of\_Long\_Journey} - \text{Hybrid\_Average\_Miles\_on\_Electricity}$
98.  $\text{New\_Battery\_Capacity\_in\_kWh} = \frac{\text{Average\_Charging\_Current} * \text{Average\_Charging\_Time} * \text{Charging\_Voltage\_in\_Mass} * \text{Battery\_Technology\_Factor}}{1000}$

### Explanation of Equations

**Charging Voltage in Mass:** This is the voltage at which the battery of a PHEV will be charging at from the wall outlet of a home. This parameter is necessary for calculating the electrical energy storing capacity of the hybrid.

**Average Charging Current:** This is the average current drawn by the battery of the PHEV during charging its battery. This current can be controlled by National Grid and therefore can be used a sensitivity parameter in the System Dynamics model. Again, this parameter is used in calculating the electrical energy storing capacity of the PHEV battery.

**Average Charging Time:** This is the time taken for the PHEV battery to charge to full power. It will be instrumental in calculating the electrical energy storing capacity of the PHEV battery.

**New Battery Capacity in kWh:** This is the total electrical energy stored (or the amount that can be stored after recharge) of a new PHEV battery.

**New Battery Capacity:** This the total energy in kWh stored in a new battery once it is fully charged. It can be obtained from the equation:

$$\text{Energy} = \text{Voltage} \times \text{Current} \times \text{Time}$$

Therefore, the formula for this parameter is

$$\frac{\text{Average\_Charging\_Current} * \text{Average\_Charging\_Time} * \text{Charging\_Voltage\_in\_Mass} * \text{Battery\_Technology\_Factor}}{1000}$$

**Effective Battery Capacity:** This parameter could be used to account for the fact that as batteries are used and recharged their capacity usually diminishes. Therefore, the new battery capacity is multiplied by a constant less than 1 to give the effective battery capacity. Nominally it is equal to new battery capacity. This parameter is made for sensitivity analysis.



**Annual Cost of Charging per Hybrid:** This is the product of Battery Capacity and the sum of Unit Energy cost and Unit Delivery Cost. This product is multiplied by 365 days to give the cost of energy used to charge the battery of one PHEV in one year.

**Battery Technology Factor:** Technological advances can lead to more efficient batteries with higher capacities. This factor will increase battery capacity and efficiency. It is a sensitivity parameter.

**Miles Covered by Gas:** This is the number of miles of a long journey that is covered by gasoline in a PHEV. When electricity in a battery is used up, the PHEV will switch to gasoline. However, if the miles covered by using electricity stored in the battery exceed the distance of the journey, then this parameter is zero. Therefore, the formula for this parameter is

IF(Hybrid\_Average\_Miles\_on\_Electricity>Average\_Distance\_of\_Long\_Journey) THEN (0)

ELSE (Average\_Distance\_of\_Long\_Journey-Hybrid\_Average\_Miles\_on\_Electricity)

**Average kWh per Mile:** This is the average kWh used by a PHEV per one mile of distance travelled.<sup>25</sup>

**Hybrid Average Miles on Electricity:** This is the average number of miles that the PHEV can travel solely on electricity stored in the battery. This value is computed from

Effective\_Avg\_Battery\_Cap\_per\_Hybrid/Average\_kWh\_per\_mile

This computation yields the number of miles travelled using a fully charged battery. The formula can be verified with the units: kWh divided by kWh/mile = mile

**Average Distance of Long Journey:** This is an estimate of the distance of a long journey travelled by car on average. It is a sensitivity parameter.

**kWh Daily Usage per Hybrid:** This is the total amount of energy used in kWh in charging the battery per PHEV. The formula for this parameter is

Hybrids\_on\_the\_Road\*Effective\_Avg\_Battery\_Cap\_per\_Hybrid

The battery capacity is in kWh of energy. This is also the energy used per Hybrid. Multiplying this figure with the total number of Hybrids gives the total amount of energy used daily per Hybrid for charging.

**kW Daily Usage:** This is the power consumed when charging the battery of PHEV. It is obtained by dividing the total energy by the charging time, since power is the rate of change of energy. Hence, the formula is

Effective\_Avg\_Battery\_Cap\_per\_Hybrid/Average\_Charging\_Time

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<sup>25</sup> (Kintner-Meyer)

**Average Cost, Change in Average and Averaging Time:** The Annual Cost of Charging per Hybrid cannot be connected in another sector due to a circular link detected by the software and is not a permitted operation. To overcome this problem, The Annual cost of charging is put into a stock called Average Cost and the value is then carried over to the other sector. Now, the program does not recognize the circular connection. The Averaging Time is set to 1, so the flow is equal to

$$\text{Average\_Cost} - \text{Average\_Cost}/1 = 0$$

Hence the stock value will not change and remain constant at Annual Cost of Charging per Hybrid

# 5. Results

## 5.1. Sensitivity Analysis

This section targets various policies that can be implemented in the model to test their effect on the number of PHEVs on the road. In order to do this, various parameters will be changed within the model and simulate the change in PHEVs over a set period of time as a result of these changes. Each change shall hereby be referred to as an experiment, and a considerable number of experiments shall be documented in this section of the report.

For example, in an experiment, the cost of PHEVs is drastically decreased, the appeal for PHEVs will increase, which will drive the growth of PHEVs on the road. Similar experiments will be documented in the next section.

### 5.1.1. Experiment 1 – Sale Time of PHEVs

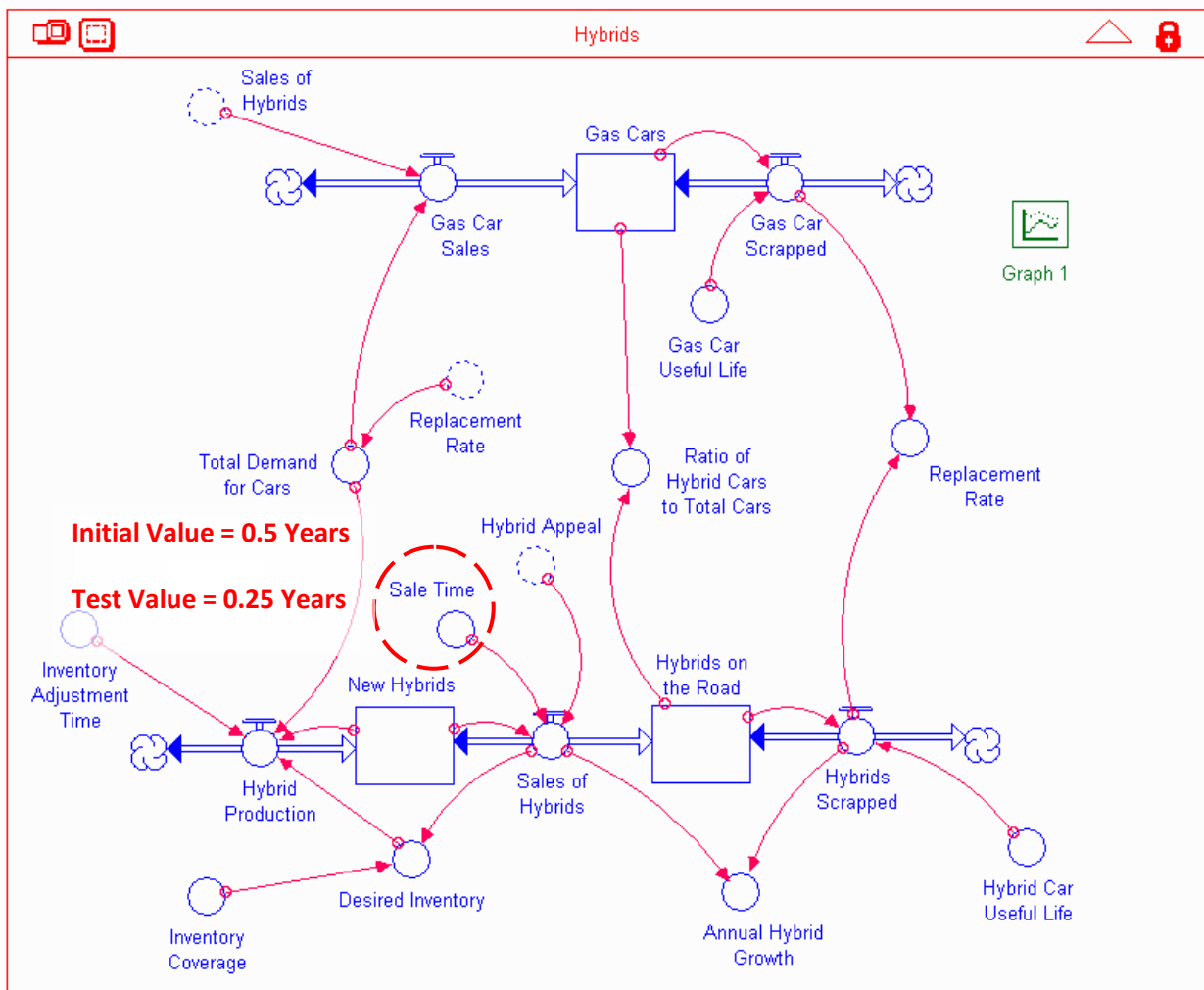


Figure 5-1 Hybrids Sector

The growth of PHEVs on the road is directly related to the sale time of PHEVs available in showrooms. Since the model includes a stock of new PHEVs that are stored in showrooms, a shorter

selling time implies that each car entering the showrooms is getting processed quickly. Therefore, for a reduced sale time, the number of PHEVs on the road is expected to increase (in inverse proportion) to a decrease in sale time of PHEVs. The initial value of sale time was 0.5 years (6 months). This implies that

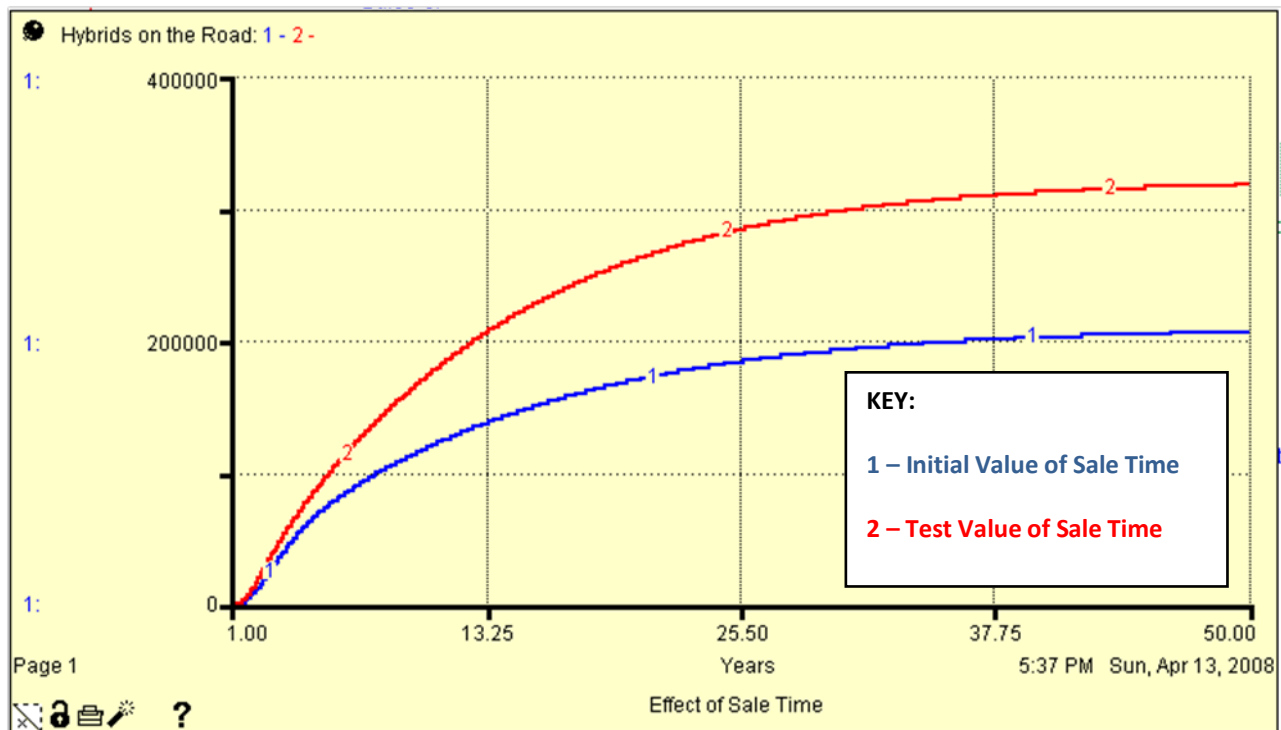


Figure 5-2 Hybrids on the Road - Experiment 1

it takes an average of 6 months to sell one PHEV car. It was decided that this time was too long and it should take an average of 3 months to sell each PHEV car, therefore the value was changed to 0.25 years (3 months). The following results were produced from this experiment.

It is evident from the results of this experiment that the hybrids on the road attain a value of around 310,000 cars within 50 year when the sale time is 0.25 years (test value). In contrast, the number of hybrids on the road within 50 years is around 200,000 when the sale time is 0.5 years (initial value). Since the total number of cars in Massachusetts has been kept constant at 330,000 in the model for simplicity, a value of 310,000 for hybrids within 50 years is ideal as it shows that the PHEVs have successfully taken off in that period of time. To conclude, the value of sale time will be reset equal to this test value, since it is more adequate and produces the more desirable result.

### 5.1.2 Experiment 2 – Battery Technology Factor

New battery technologies are investigated today in many applications, including PHEVs. Research groups are working to find ways to increase battery capacity and life so that PHEVs require less frequent charging meaning less electricity will be used. The model has accounted for the fact that there may be improvements in battery design for PHEVs using a variable called *Battery Technology Factor*.

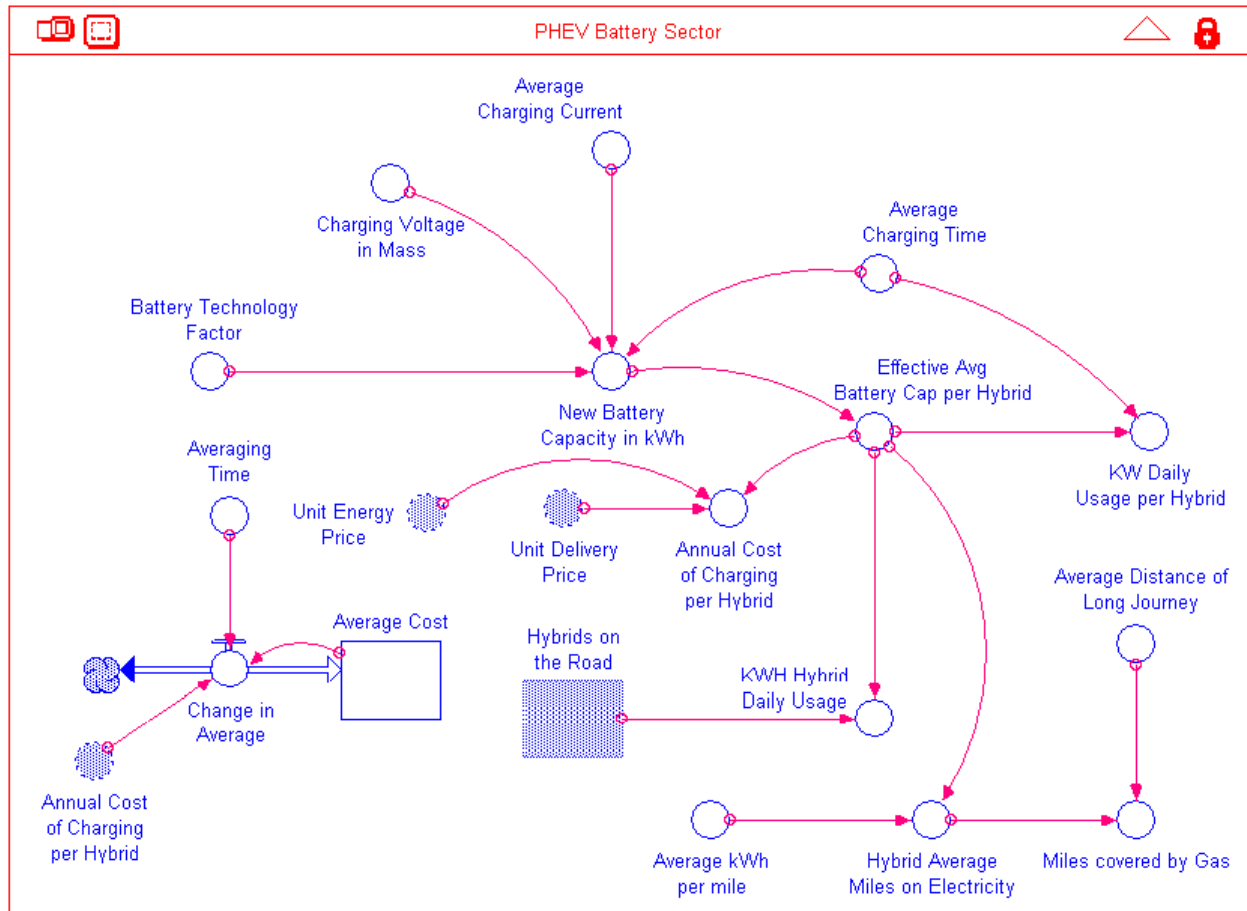


Figure 5-3 PHEV Battery Sector - Experiment 2

The battery technology factor is nominally set to 1. Any improvements in battery capacity will cause changes in the cost of operating a hybrid as well as the number of miles that can be travelled on average without gas. To see the effect that a change in battery technology has, *Hybrid Appeal* will be observed for changes. This is because changes in costs and electricity mileage will only affect the attractiveness of a PHEV. The graph below shows how *Hybrid Appeal* behaves with a nominal value of 1 for *Battery Technology Factor*.

The parameter Battery Technology Factor was created to model the behavior of the system when technological advances bring battery capacities up and therefore Hybrids can run longer on Electricity. In the model an increase in the battery technology factor leads to an increase in electrical capacity of the battery and a decrease in operating cost as well, since the batteries would become more efficient. The following experiment was conducted: the model was simulated using three values for battery technology 1, 2, and 0.5. 1 represents a nominal value that depicts the behavior when new batteries are just put to the market. 2 Represents the behavior when battery technology improves and causes the electrical capacity of the battery to increase. However, this is accompanied by a decrease in operating cost since the battery is more efficient and needs less charging. 0.5 represents the scenario

when battery performance slowly starts to diminish. For example, batteries might fail. All of these scenarios are simulated and the results are shown below.

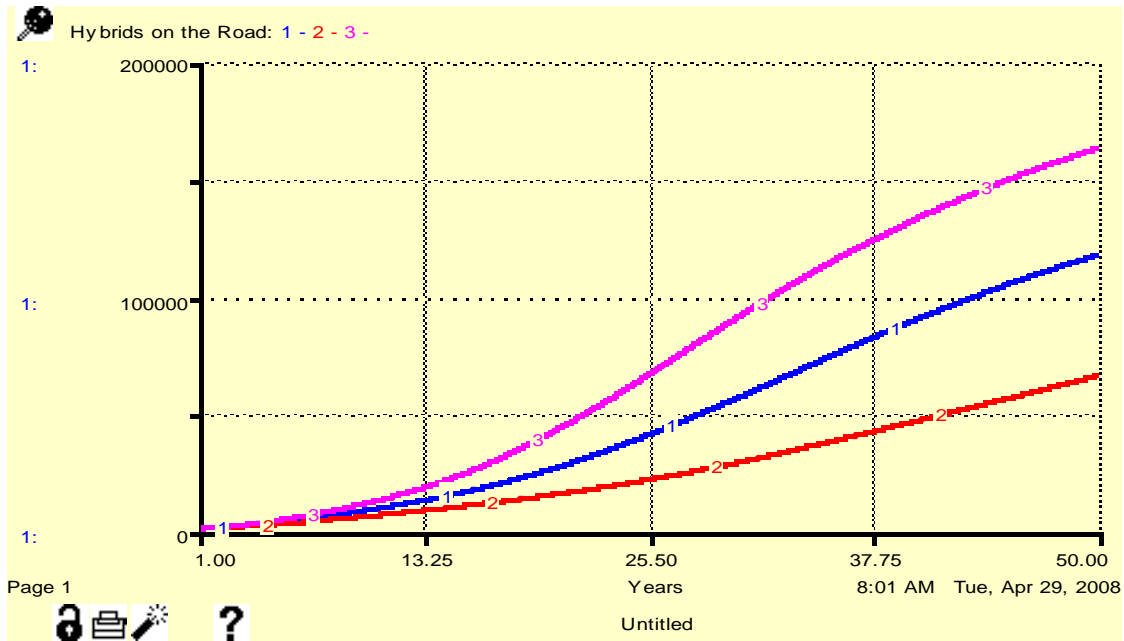


Figure 5-4 Graph showing Behavior of PHEV numbers when Battery performance changes

The blue line represents the behavior due to the nominal value. The red line represents the behavior due to Battery Technology at 0.5. The pink line represents the behavior when battery technology is increased to 2.

As can be seen an increase from the nominal value brings about an increase of the number of PHEVs. This is because the capacity of the battery increases and simultaneously the cost of operating decreases due to increase in efficiency.

The red line shows that if the Battery Technology Factor decreases to half the nominal value, PHEV numbers are almost halved as well in 50 years. The growth rate is also much slower. This is because costs increase and the electrical capacity decreases.

### 5.1.3. Experiment 3 – Changing Hybrid Operating Cost

In this section, an experiment of changing Hybrid Operating Cost and observing its effects will be conducted. The formula for Hybrid Operating Cost is

$$(\text{Annual\_Maintance\_Cost} + \text{Average\_Cost}) * \text{Effect\_of\_Gas\_Miles\_on\_PHEV\_Opearting\_Cost}$$

With initial values for the parameters noted above the results are as follows.

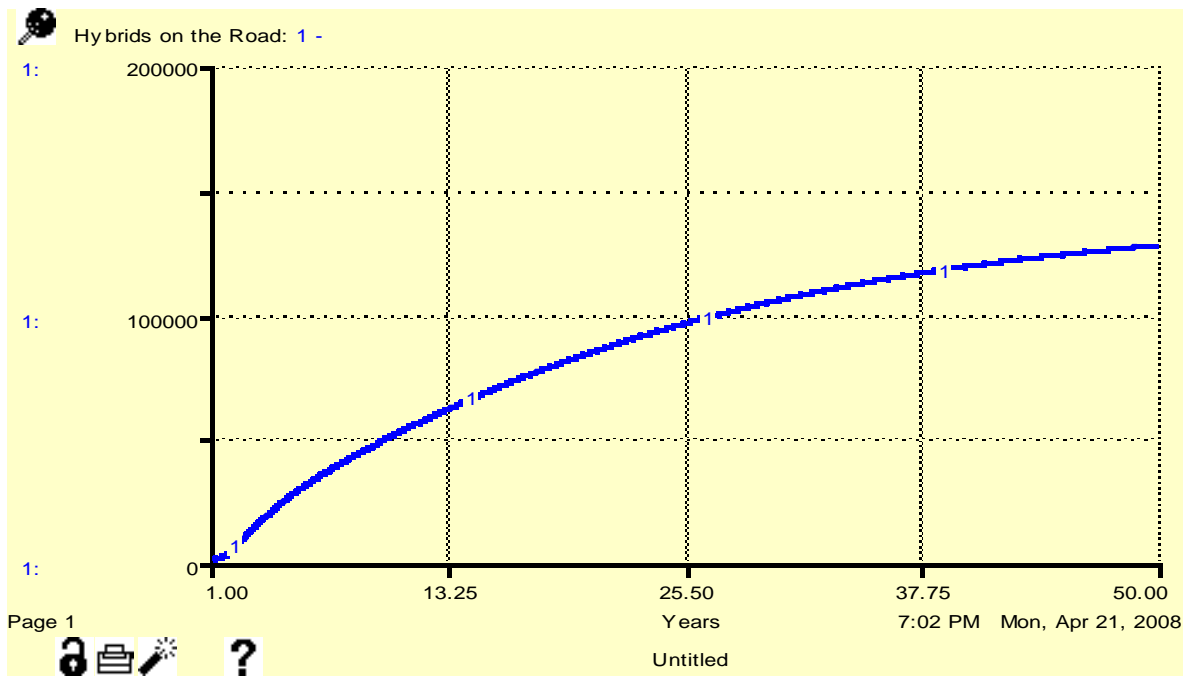


Figure 5-5 Hybrids on the Road - Experiment 3a

As can be seen, the number of Hybrids increases at a decreasing rate. The tendency of the growth is to level off to a certain value. Next it is to observe what happens when the operating cost is doubled.

$$2 * (\text{Annual\_Maintance\_Cost} + \text{Average\_Cost}) * \text{Effect\_of\_Gas\_Miles\_on\_PHEV\_Opearting\_Cost}$$

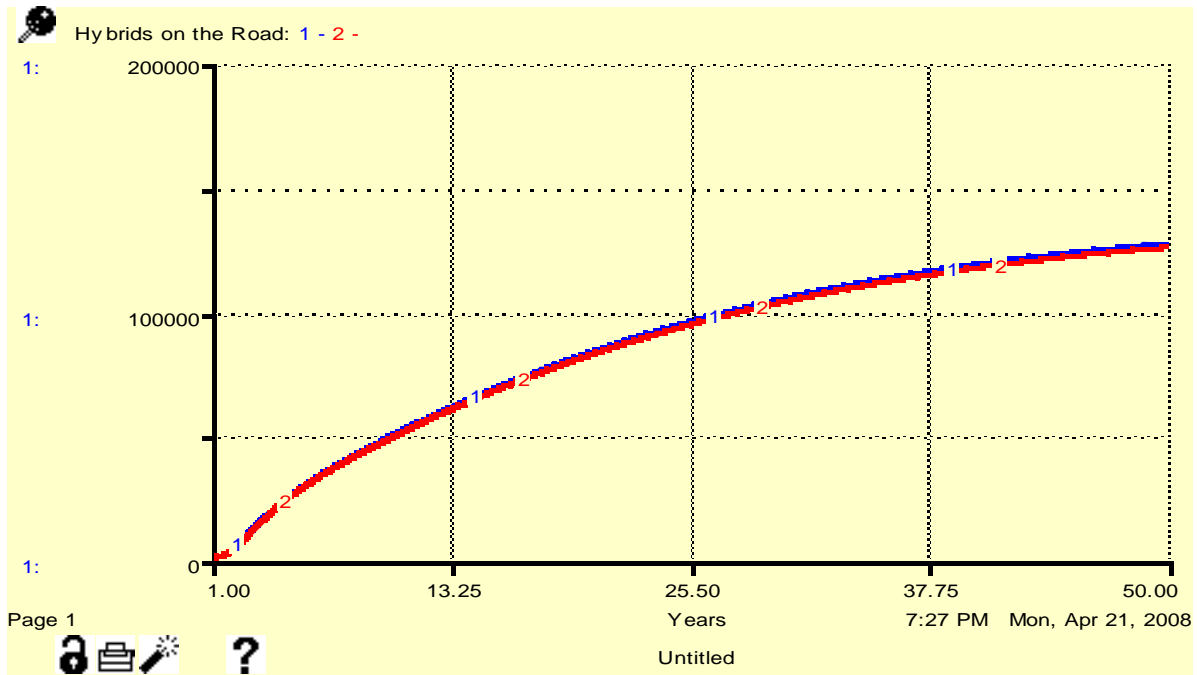


Figure 5-6 Hybrids on the Road - Experiment 3b

As can be seen there is very little change when the operating cost is doubled. It slows down the growth of hybrids but this decrease is not very significant. The following graph shows the result when the Operating Cost is increased drastically by a factor of 10.

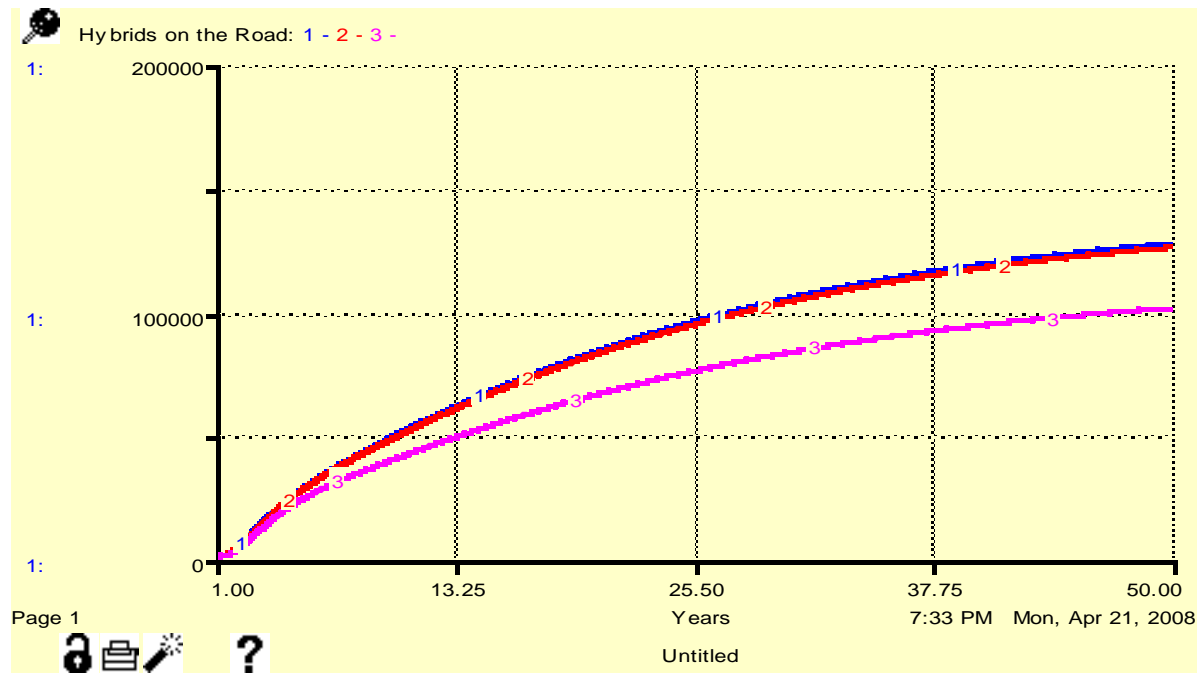


Figure 5-7 Hybrids on the Road - Experiment 3c

The multiplication of Hybrid Operating Cost by a factor of 10 brings about a significant change in the number of Hybrids. The growth is slowed down significantly and also comes to a steady level that is lower than before.

Hybrid Operating Cost will not affect the growth of Hybrids significantly unless the change is a drastic one. Thus, the effect weighting is not very high for this parameter.

#### 5.1.4. Experiment 4 – Changing Average Charging Current

The current at which the PHEV batteries get charged is one that is regulated by National Grid. Only a certain amount of maximum current can be supplied. However, it is worthwhile to see what would happen if the charging current were increased.

The graph below shows nominal PHEV growth with nominal charging current.





Figure 5-8 Hybrids on the Road - Experiment 4a

The graph below shows what would happen if the charging current levels were increased if the battery specifications were changed. The Average Charging Current is now increased to 20A.

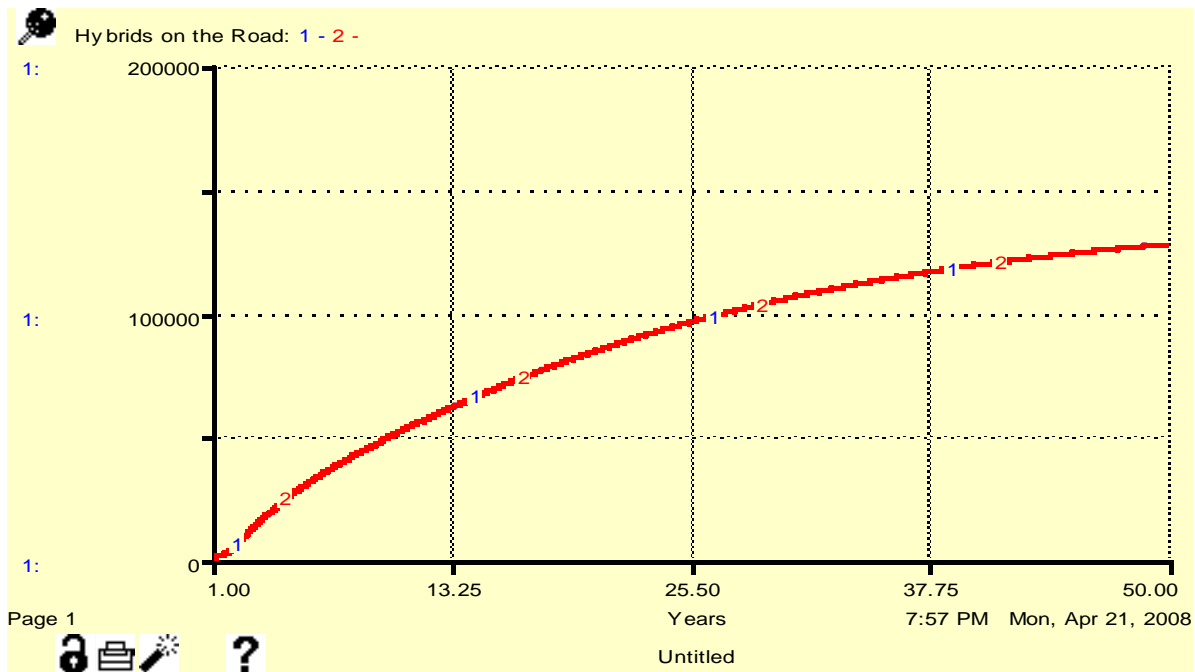


Figure 5-9 Hybrids on the Road - Experiment 4b

It can be deduced from the above graphs that changing the charging current will not affect the growth of hybrids very significantly.

### 5.1.5. Experiment 5 – Changing Average Charging Time

Average charging time is the time taken to recharge the PHEV battery fully. This charging time may change depending on many factors such as manufacturers and technological advances.

The following graph shows what behavior is produced with nominal charging time.

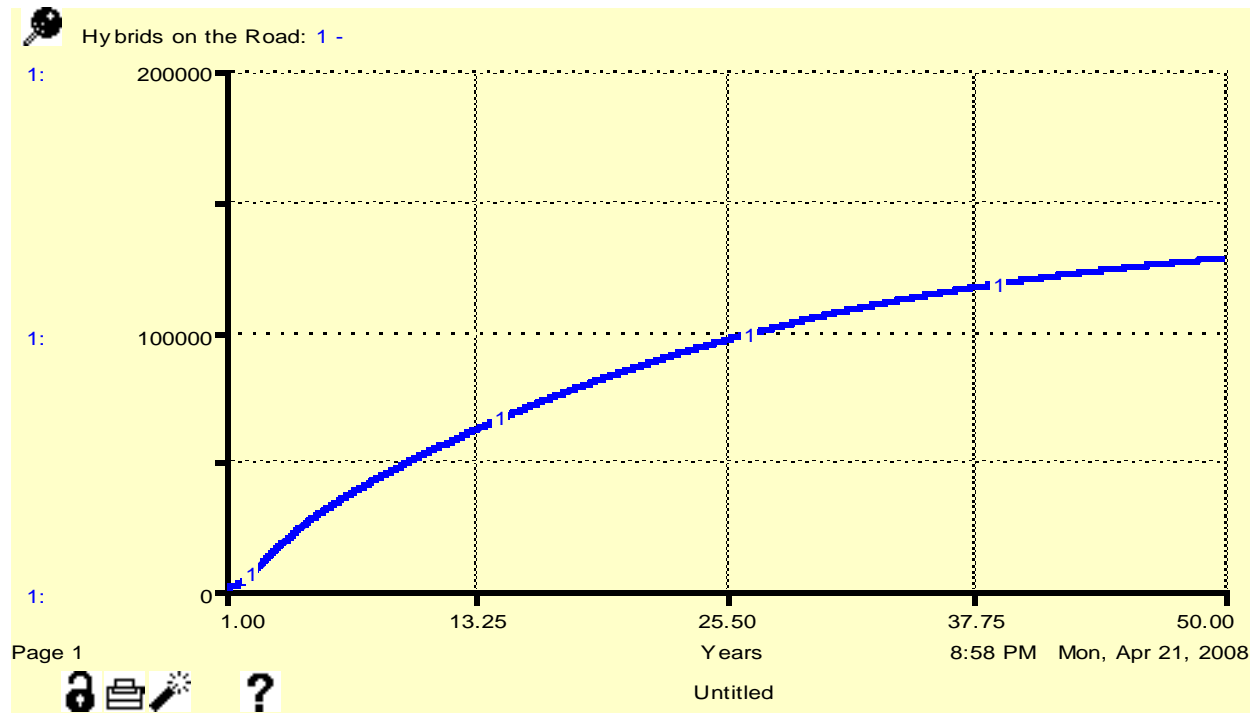
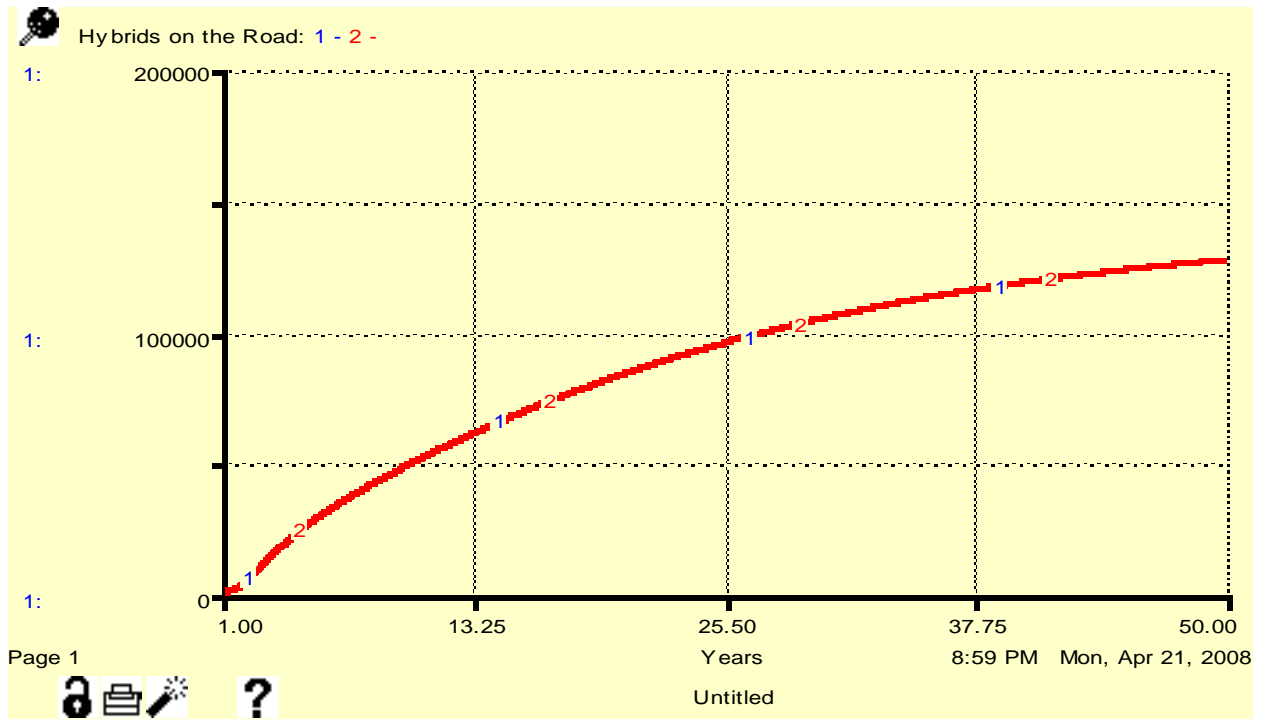


Figure 5-10 Hybrids on the Road - Experiment 5a

The figure below shows the number of PHEVs on the road when the Charging Time is increased from 4 to 8 hours.



**Figure 5-11 Hybrids on the Road - Experiment 5b**

The red line which denotes the new behavior superimposes the nominal behavior. This means that Charge Time will not have such a great effect on the number of PHEVs on the road. Therefore, if any battery changes occur, it will not cause any significant change in the way people feel about PHEVs, although there will be a higher load on electricity distribution companies such as National Grid.

### 5.1.6. Experiment 6 – Normal National Grid Incentive

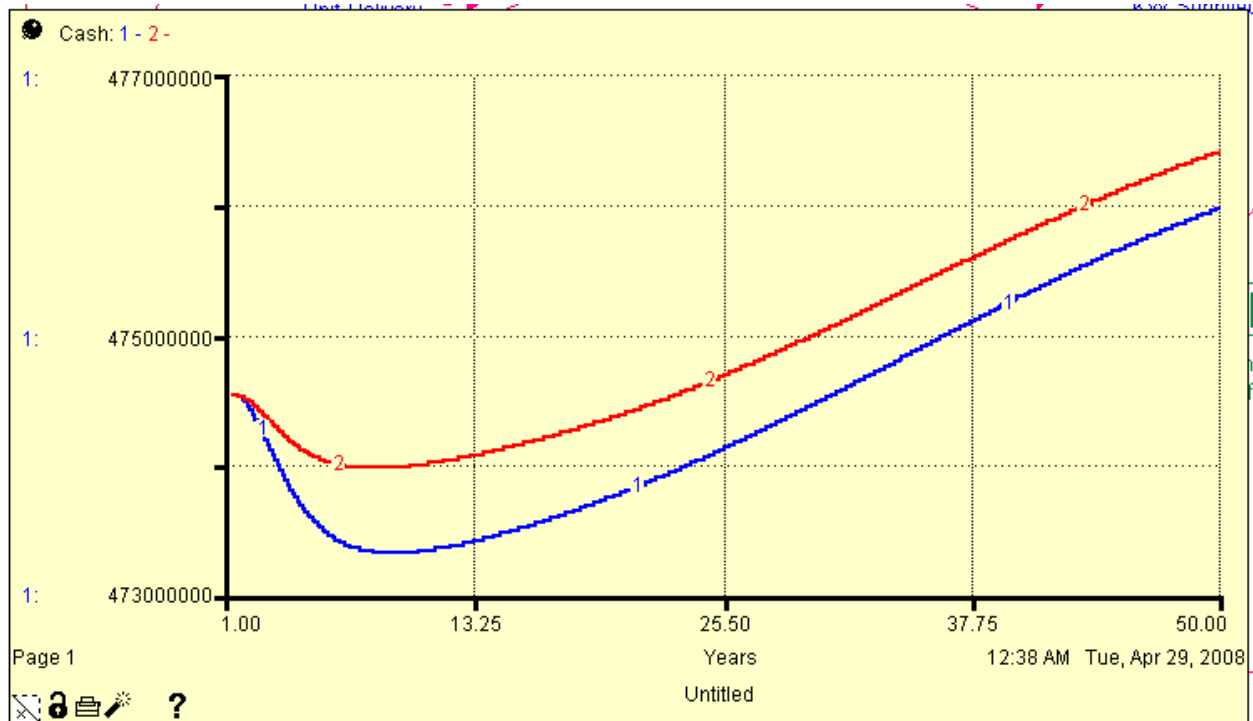


Figure 5-12 Cash - Experiment 6

According to the model structure, National Grid presents cash discounts and rebates to consumers that may buy or have bought PHEV's. The normal amount of incentive that National Grid may offer is a parameter that can be subjected to some sensitivity analysis. It can be seen in the figure that simply halving the normal incentive offered by National Grid in total (from \$1 million to \$0.5 million) slightly increases the cash acquired, so that it attains a final value of around \$476.4 million, which is less than the normal value of \$476 million normally attained in the modeling period of 50 years. The value of \$1 million will be kept for normal incentives offered by National Grid, since there is not a significant impact of this doubling cost on the overall cash acquired.

### 5.1.7. Experiment 7 – Variation of Car Life: PHEV and Gas Cars

This experiment looks at the average useful life of the cars and if changing the life will affect the model. The average life of a gas car (Gas\_Car\_Useful\_Life) is set to be 15 years and the average life of a PHEV (Hybrid\_Car\_Useful\_Life) car is set as 20 years. This number is an average and took into account normal wear and tear on a car that was constantly used. The value for gas cars is lower because it was assumed that gas car's engine would die out at that time versus the combination or electric motor and gas engine of the PHEVs. In the first round of experiments, the life of hybrids is changed to see if more would sell. For the second round, the life of gas cars was changed, observing how the system reacted and how it affected hybrid sales. The variation will be as follows: the standard life in the model, then double life and finally half life. An analysis will be performed to see how the model behaves and how each stock of car changes in response to the variation and ensure that the system behaves as predicted.

Gas Car Life:

Trial 1: Normal 15 year life, 33,000 cars on the road now, hybrids set at 20 years

Trial 2: Double Life 30 years, 33,000 cars on the road now, hybrids set at 20 Years

Trial 3: Half-life 7.5 years, 33,000 cars on the road now, hybrids set at 20 years

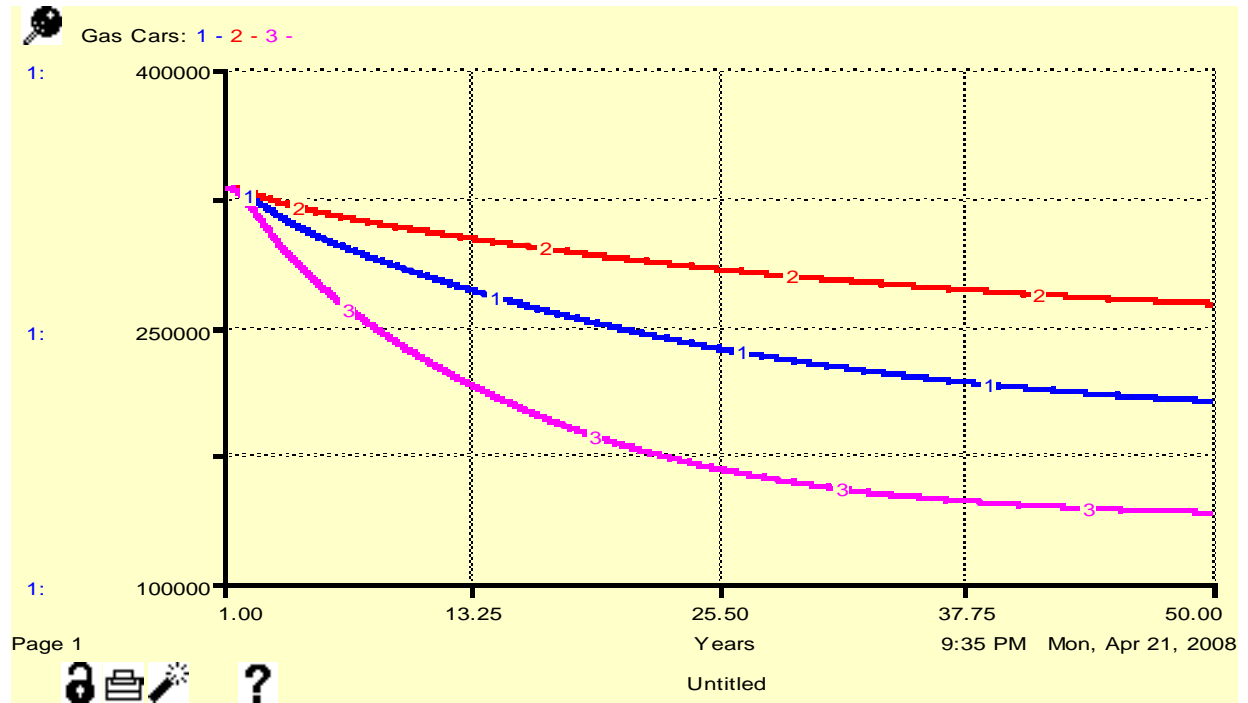


Figure 5-13 Gas Cars - Experiment 7a

The results show that the speed at which gas cars are replaced depends on their useful life. A higher life means a longer use period and they are not as quickly replaced as observed in trial 2. Reducing the gas cars' useful life by half, results in gas cars being replaced at a rapid pace. Trial 3 starts with 33,000 on the road at year 0 and ends with around 12,000 at year 50. Compare this with Trial 1, where at year 50 there are an estimated 18,000 gas cars. There is a decrease of nearly 6,000 cars over the same time frame signifying that the decrease in life will affect the replacement rate. The growth of hybrids correlates to the life of gas cars, as their life increases, the growth declines. Trial 2 has a useful life of 30 years; the model shows that the growth of hybrids is reduced from 750, hybrids sold at its peak, to 250 hybrids sold at its peak. That is a significant decrease in the amount of hybrids that are sold.

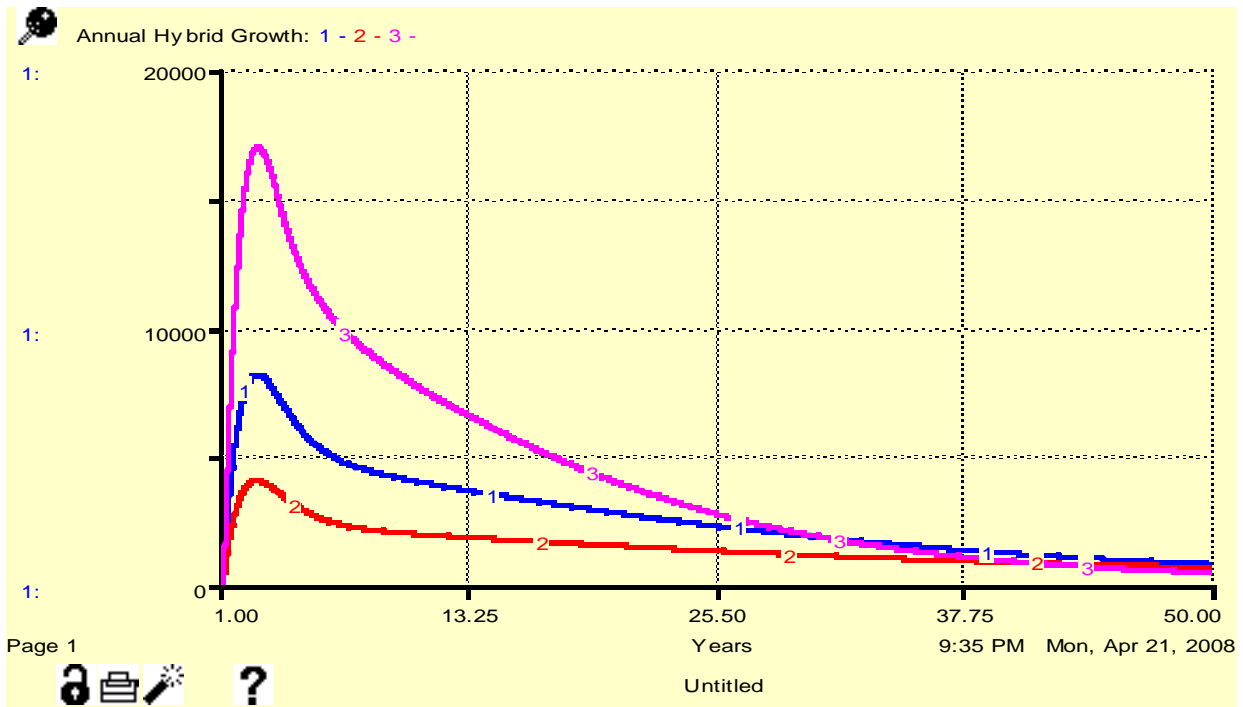


Figure 5-14 Annual Hybrid Grown - Experiment 7b

Hybrid Car Life:

Trial 1: Normal 20 year life, gas cars set at 15 years

Trial 2: Double Life 40 years, gas cars set at 15 years

Trial 3: Half-life 10 years, gas cars set at 15 years

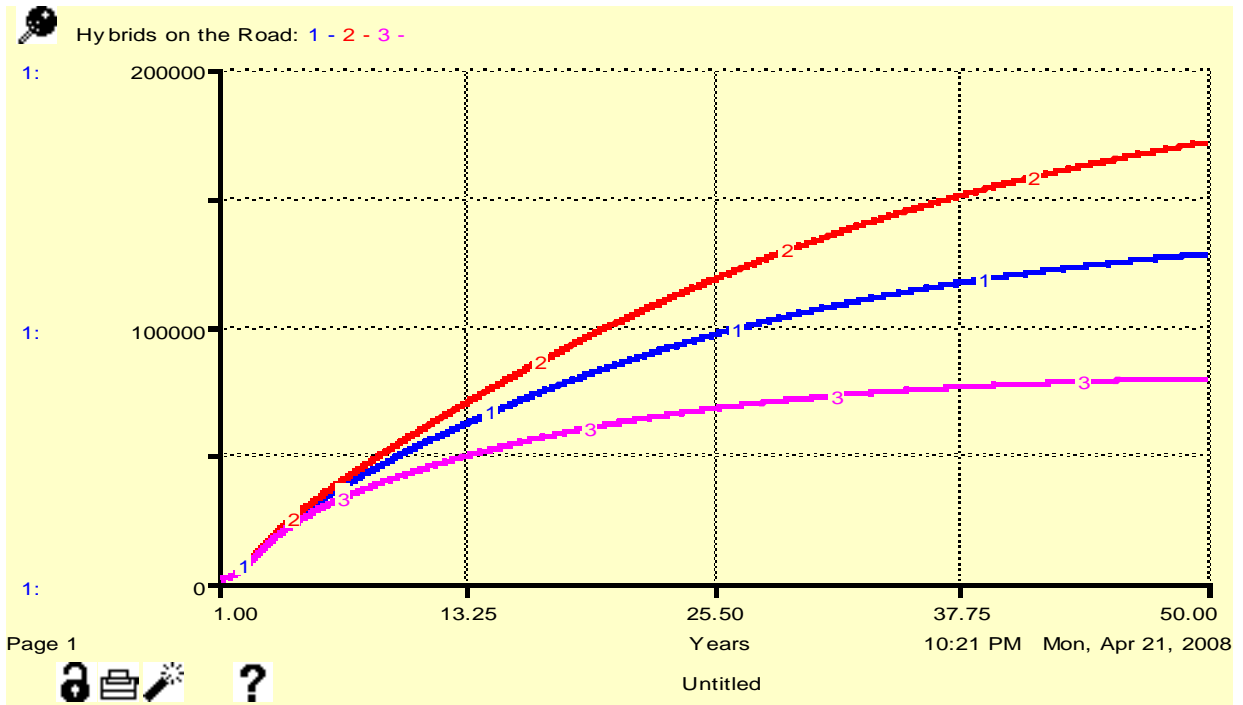


Figure 5-15 Hybrids on the Road - Experiment 7c

The hybrids on the road increase with the average useful life. The model shows how the system will behave if the life of cars is similar to these values. The shorter life means that there will be less sales and less growth. The consumer base is reluctantly chose a car that has a lower useful life than a gas car, but will do so as the time continues

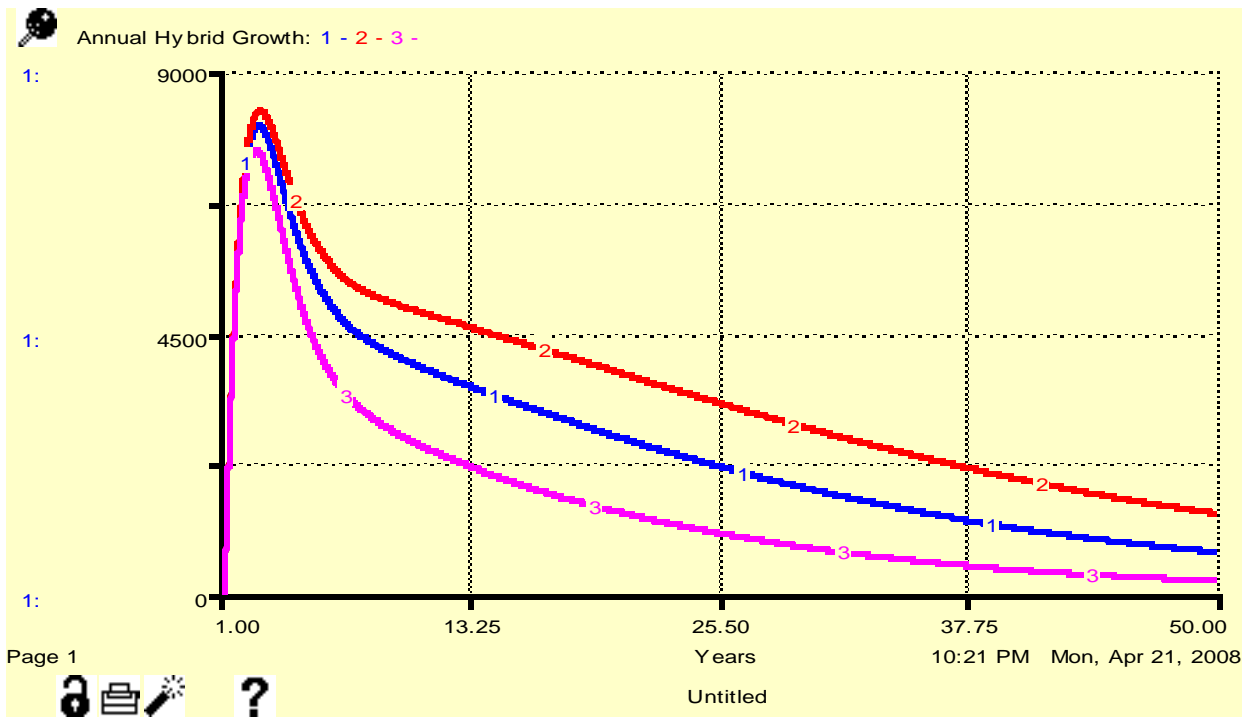


Figure 5-16 Annual Hybrid Growth - Experiment 7d

When an experiment was performed with the useful life of the cars, the affect on the growth of hybrids was noted for the change in certain parameters. The main concern with this experiment was to ensure that hybrids would continue to grow even if the life of the cars was changed. Another concern was if the useful hybrid life was too short, the system will not function properly and continue its growth. The testing showed that if the average life of a hybrid car was kept between 20 to 40 years that these cars would be chosen over the gas cars with their average life of 15 years. This life span also allows the system to reach it sustainability. Having a useful life of less than 10 years would not be ideal and hybrid cars will not grow in the same manner nor be as successful.

### 5.1.8. Experiment 8 - Variation of Diffusion Effect:

The diffusion effect (diffusion\_effect\_on\_hybrids) is the graphical parameter that is used to represent word of mouth amongst consumers. This series of experiments will change the graphical function of this parameter and demonstrate if and how this parameter will affect the overall appeal of the hybrids. The trials will be as follows: trial 1 shall be the control with all parameters left with the original values, the second will be to inverse the graphical function to simulate the opposite and the final will be expanding the values from 0-2 instead of 0-1.

Trial 1: normal graphical function

Trial 2: inverse of normal function simulates hesitation amongst consumer

Trial 3: enlarged normal version, simulates great interest by the consumer in PHEVs



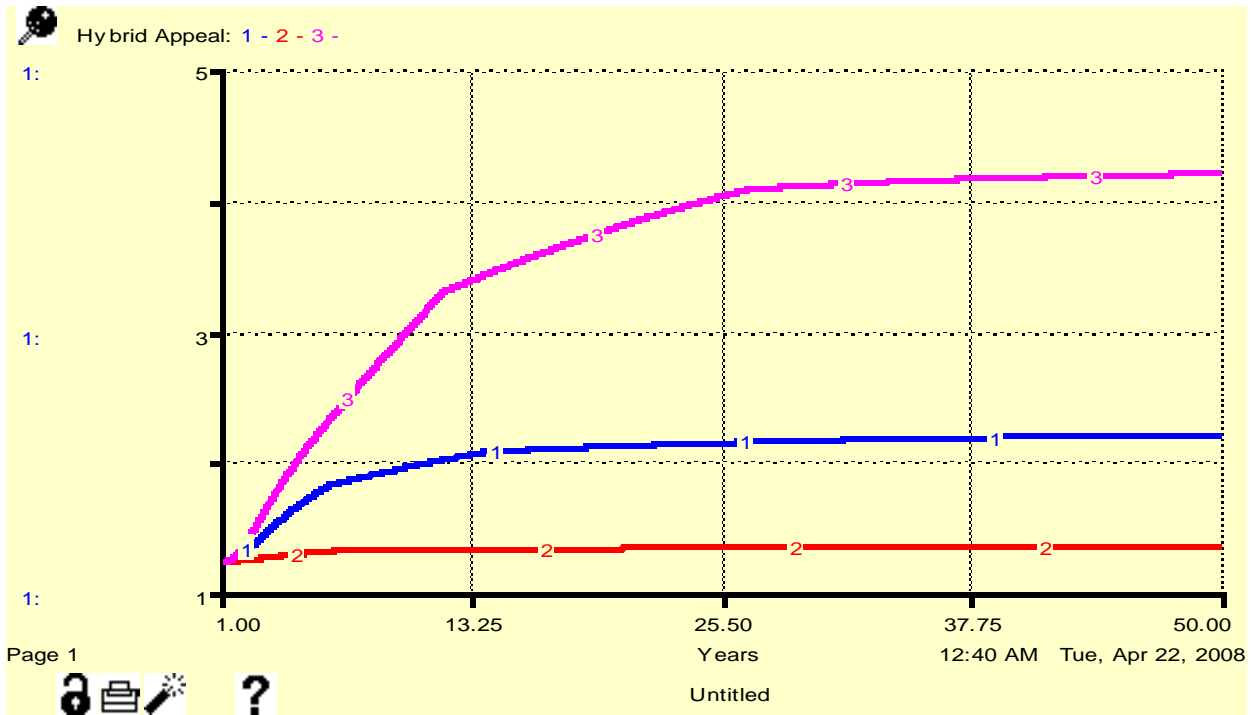


Figure 5-17 Hybrid Appeal - Experiment 8a

The model was run three times, the two experiment sections show the contrast of the model. Trial 2 shows what would happen if word-of-mouth failed to catch on. People saw the PHEV cars but were not really drawn to them. The model simulates minimal hybrid appeal from this experiment and hybrids are not as easily sold to consumers. Trial 3 shows the opposite of trial 2 where there is great buzz stirred by the PHEVs. They are extremely popular among the consumers and this helps boost the number of hybrids on the road fairly quickly.

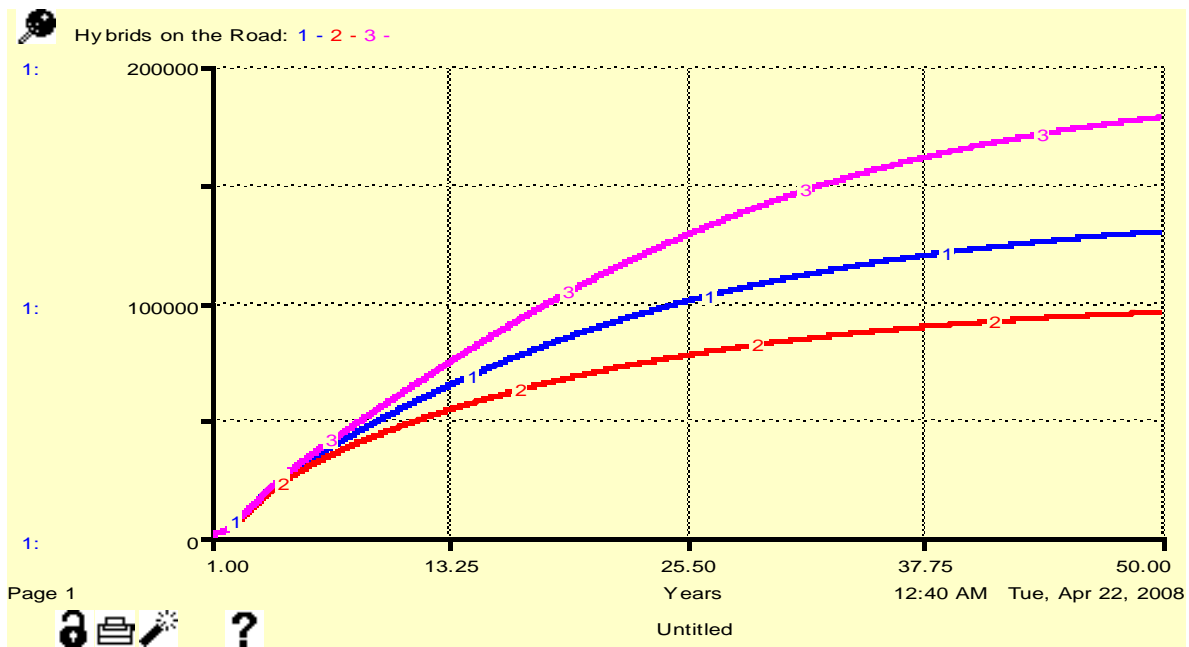


Figure 5-18 Hybrids on the Road - Experiment 8b

The Diffusion effect represents word of mouth among consumers. To achieve the optimal result, the test shows that this is a key factor in getting PHEVs to succeed. The manufacture of the PHEVs must put the right resources into advertising the PHEVs and target the correct group. If done correctly, these experiments show that targeting the right group can boost sales, but failure to capture the right group will cause a delay in the sales.

### 5.1.9. Experiment 9 – Variation of Operational Cost of Gas Cars

In this experiment, the operational cost was changed for gas cars. Doing so demonstrates how the system would react to an outside stimulus such as change in oil prices. The operational cost for gas cars (Gas\_Car\_Operational\_Cost) were affected by the price of gas, the average amount of gas used (Annual\_Cost\_of\_Gas) and then a constant operational cost (Annual\_Maintenance\_Cost) that applied to both types of cars; this included normal car maintenance, tires wiper blades and other items generic to a car. This experiment was to change the total operational cost for gas cars by changing the price of gas and the mileage. By looking at the hybrid appeal and then the number of each type of car, observations can be made on how the model reacts. This shows that if there was a change in how appealing the hybrids would be compared to the gas cars given these changing variables.

These were the trials that were set:

Trial 1: Initial value, all values held constant

Trial 2: Gas prices doubled, other sectors constant

Trial 3: Gas prices tripled, others constant

Trial 4: Double efficiency of gas cars

Trial 5: Triple the efficiency of gas cars

Trial 6: Gas is free

Trials 2 and 3 showed what would happen if gas prices increased first double the current \$3.19 then triple the amount. These trials represent the current economic and social state that Americans are currently in. There is the possibility that gas prices could double or triple at a given point. Trial 2 and 3 show how the system would respond in regards to the purchase of gas cars.

At \$6.38, the appeal for hybrids is noticeably greater than at the set rate. The appeal goes from 1.5 to just over 2.5 for this price range. When the gas price is tripled, the change is not as noticeable as when doubling, but there is an increase in the hybrid's appeal. Trials 2 and 3 show the direct connection between the gas prices and the appeal of hybrids. As the gas prices increase the hybrid cars will become more appealing to the population.

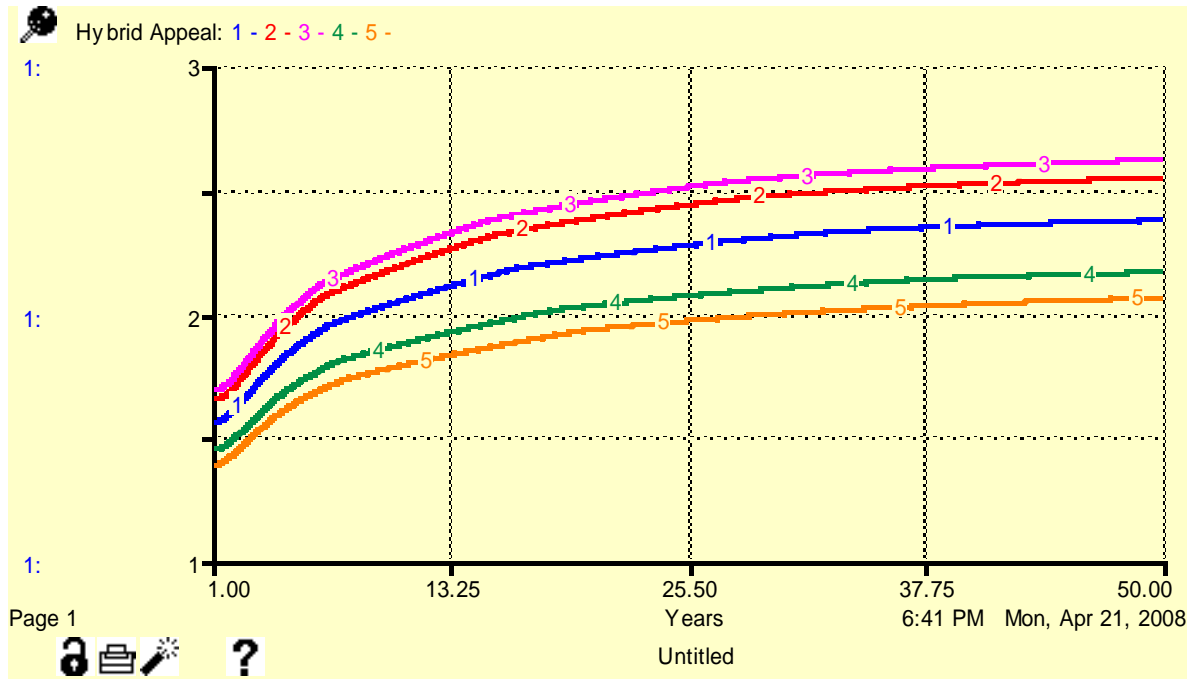


Figure 5-19 Hybrid Appeal - Experiment 9a

Trials 4 and 5 represent the possibility that newer gas cars are more efficient, that use less gas to achieve the same mileage. An assumption is made that the new cars would be twice and then three times as efficient as the current cars on the road. Instead of using an average of 541 gallons per year, the cars would use 270 gallons per year and then 180 gallons per year. Trial 4 represents cars that are twice as efficient. The model shows that the hybrid appeal does not rise as quickly as it did before ranging from about 1.5 to 2.2 for the time frame. This tells that the gas cars still maintain some attraction and some consumers are still buying those cars. For trial 5, hybrid appeal is the lowest of all trials. The appeal goes from 1.5 to just above 2. At this point, gas cars still maintain a limited hold on the car market; however they are still being replaced by hybrid cars.

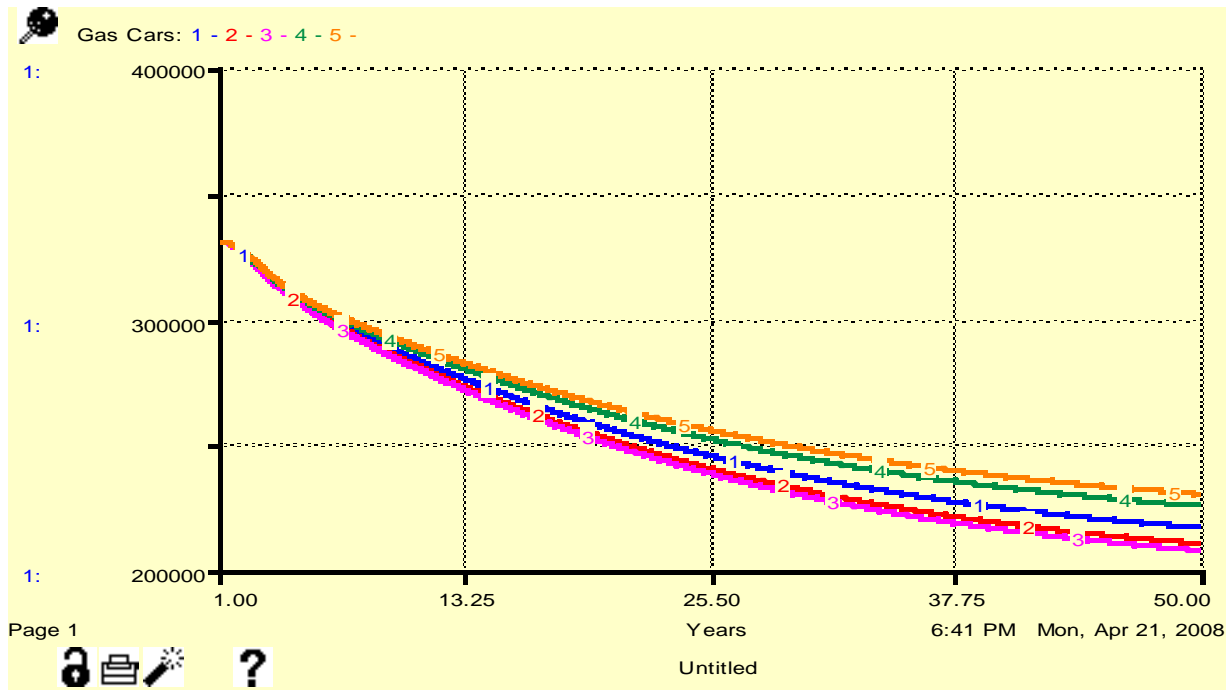


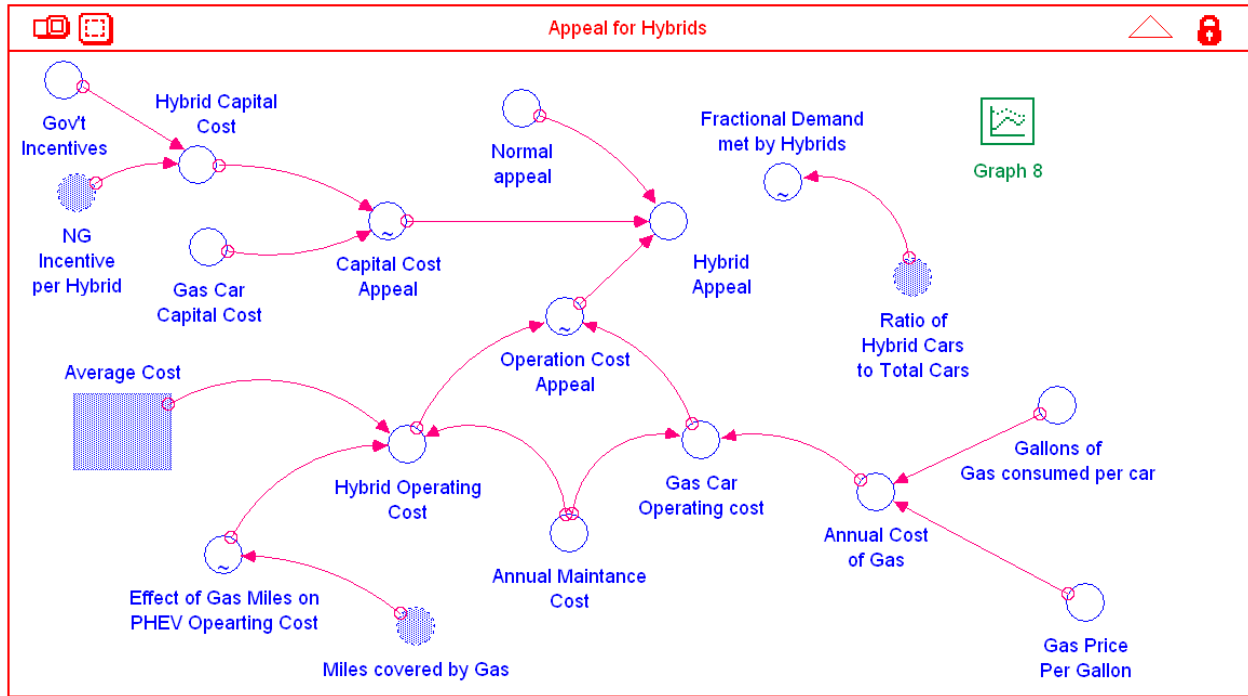
Figure 5-20 Gas Cars - Experiment 9b

Variations in gas prices and efficiency of gas cars directly affect the hybrid appeal. As the operation of gas cars becomes more expensive, the hybrid appeal goes up and as the efficiency of these cars increase, the appeal goes down. The experiment shows that gas cars still have a limited appeal depending on gas prices and the mileage of the car. Hybrids will still have a high appeal due to their overall lower operational cost.

#### 5.1.10. Experiment 10 – Variation of Hybrid capital Cost

The Hybrid capital cost (Hybrid\_Capital\_cost) parameter is the cost that a consumer pays out of pocket to buy a brand new PHEV. The initial value for this parameter is set at \$30,000, the current estimated MSRP of a Chevrolet Volt. This parameter is effected by two factors, Government Incentives (Gov't\_Incentives) and National Grid Incentives (NG\_Incentives). These factors reduce the capital cost of the hybrids; the government will offer a tax break and National Grid will offer a discount based on the money that is earned from the charging of these hybrids. This experiment focused on the capital cost of

the cars. By changing the capital cost, observations can be made on how this impacted the ownership (Hybrids\_on\_the\_Road), appeal (Hybrid\_appeal) and the profits for National Grid (Cash).



**Figure 5-21 Appeal of Hybrids Sector - Experiment 10a**

To test consumer reaction to changes in price, the price is set to these values: \$0, \$15,000, \$60,000 and \$300,000 (ten times the MSRP). The model ran for the standard time of 50 years, with the cost being fixed at those rates.

Trial 1 was the control cost, \$30,000.

Trial 2 was set at \$0 to see if the model would collapse.

Trial 3 was \$15,000, half the MSRP.

Trial 4 was \$60,000, double the MSRP.

Trial 5 was \$300,000, ten times the MSRP.

The first graph represents the effect on hybrids of the different prices. The first trial demonstrates the overall predicted outcome. At \$30,000 the hybrids will grow and eventually replace all the gas cars. For the next trials, 2 and 3, there is rapid growth that surpasses the growth of trial 1. For trial 4, there is growth but it is decreased greatly, at year 50, there are less than half as many hybrids on the road then compared to trial 1 (77,000 versus 230,000). For trial 5 the growth rate is extremely

decreased, by year 50, there are just under 6,000 cars compared to nearly 230,000 in trial 1.

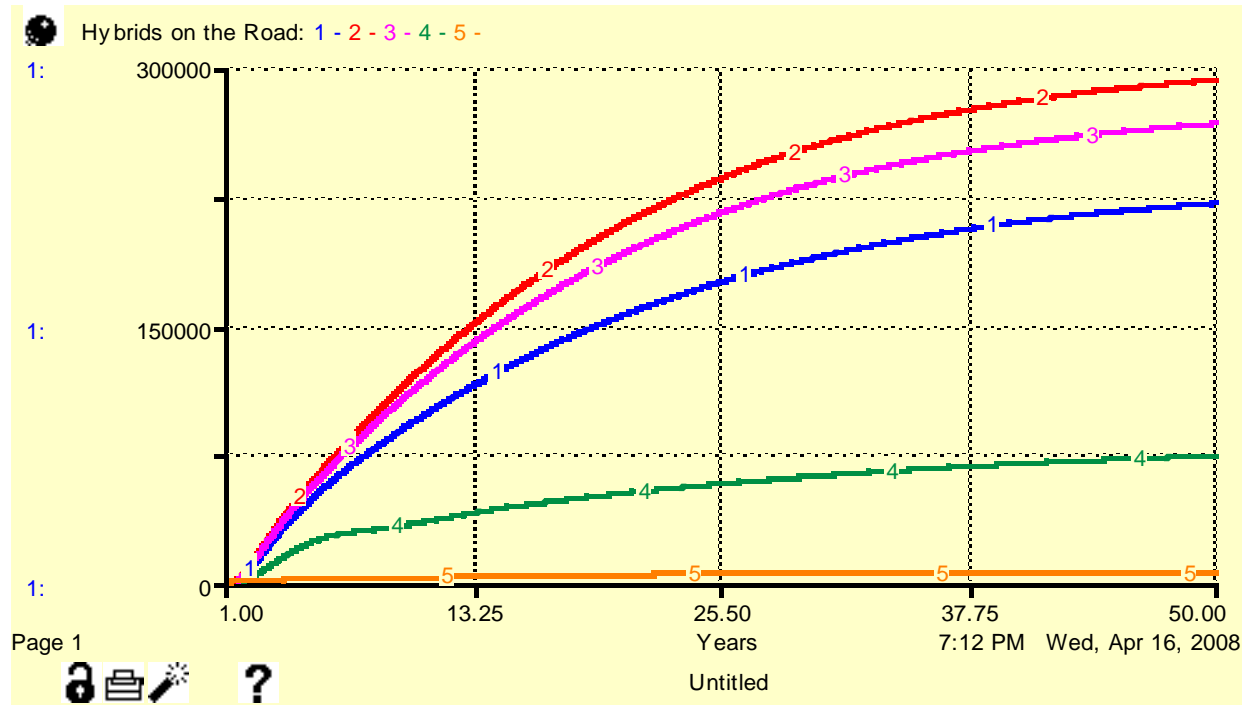


Figure 5-22 Hybrids on the Road - Experiment 10b

The second graph shows the cash of National Grid for each of the trials. Their cash directly corresponds to the number of hybrids on the road, more hybrids means more hours spent charging meaning more electricity sold. During most of the trials, this behavior is seen, however during trials 4 and 5 there is a change. Trial 4 shows almost no growth while trial 5 shows an actual decrease in the cash. For trial 4 the price was at &60,000, the cash was 90 billion compared to 160 billion for trial 1. Trial 5 there was actually a decrease in cash, ending with 94 billion compared to 95 billion. Both these trials show that with the prices at such high levels, hybrids do not sell well and the result is that the electric company does not sell as much electricity and will not gain if the prices are so high.

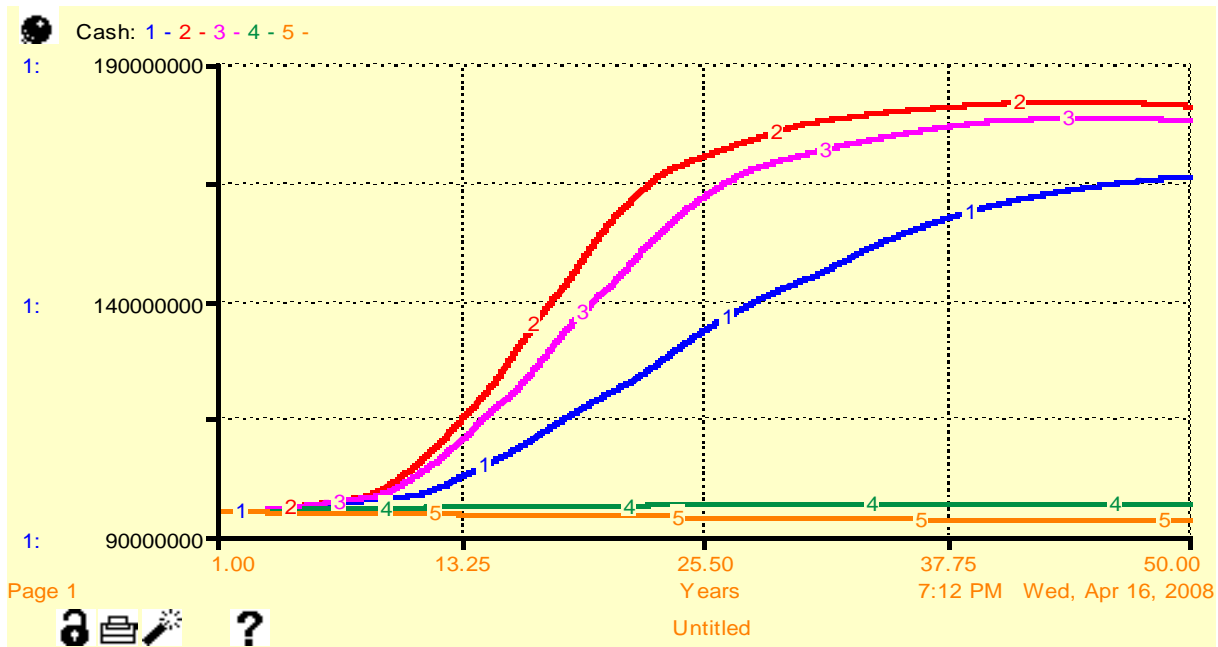


Figure 5-23 Cash - Experiment 10c

The experiment shows that the model is sensitive to the price of the cars. Set the price too high and very few will be bought and there will be less cash for the electric companies. Trial 1 was a control, the MSRP, with a gradual increase. Trial 2 and 3 the price was set lower, there is more rapid growth and a larger cash amount for National Grid. Trials 4 and 5, the price was set higher, there was noticeable decline in the growth of hybrids cars and the cash that National Grid received. With higher capital cost for hybrids, a dramatic change from how trial 1 behaved is seen. The capital cost of hybrid cars must not be set too high or the system risk becoming a failure with no/limited growth of hybrids.

### 5.1.11. Experiment 11 – Variation of Gas Car capital Cost

PHEVs offer an alternative to the traditional gas car because they are cleaner and cheaper to run. However, gas cars at the beginning of the model are still the favorite among the populous. Modifying the price of gas cars would show how the system behaves if the chief competitor's price changed. A key outcome to test is whether or not lowering the price would still attract people to hybrids and if raising the price would push people to buy hybrids faster. To test this, the following experiment is performed.

- 1) Trial 1 was the control cost, \$17,000.
- 2) Trial 2 was set at \$1 to see if the model would collapse.
- 3) Trial 3 was \$8,500, half the MSRP.
- 4) Trial 4 was \$34,000, double the MSRP.
- 5) Trial 5 was \$170,000, ten times the MSRP.

The amount of gas cars is direct relationship to the capital cost of the gas cars. Trial 2 and 3 the price was at \$1 and \$8,500 respectfully; for both the rate at which the gas cars declined was dramatically lower than the control rate. With trial 2 (\$1), there was almost no decline, only very slowly, although this is very unrealistic and used only to test if the model would collapse. Trial 3 (\$8,500) the decline was slower but more prominent than trial 2. This is more realistic, car companies and retailer may lower prices in order to sell off the remaining gas cars as they transition to an alternative energy car. The model shows that this will still draw consumers to purchase gas cars over hybrids, but eventually consumers will transition to the hybrids.

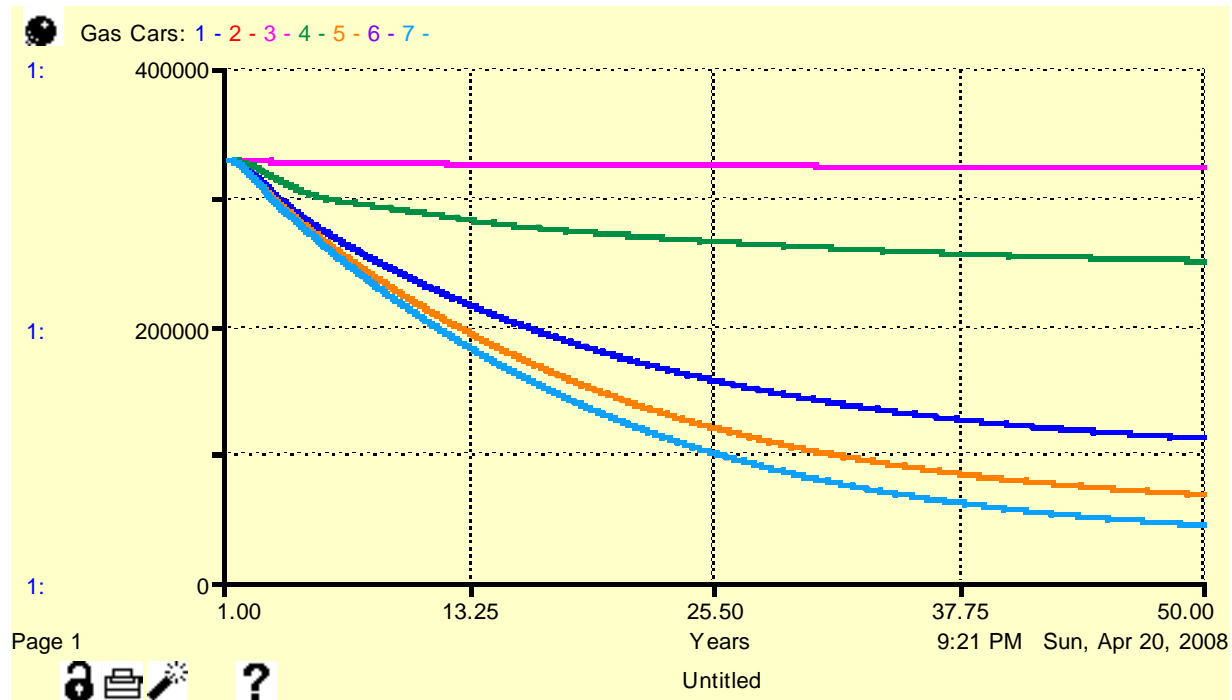


Figure 5-24 Gas Cars - Experiment 11a

Trials 4 and 5 show what happen if the prices increased. This is under a different assumption about the model. Assuming that gas cars have become more of a commodity and they are not as vital as they were in the years past. This allows producers and retailers to charge a greater price. The end result is a faster decline in the number of those cars on the road. A few do remain as collectors' items but the vast majority has been taken off the road. Trial 4, the price was double the current one (\$14,000) the rate at which cars were replaced was greater. Then in trial 5 this was even faster with the price set at \$170,000.

The gas car will eventually be replaced, at which rate, depends on the price of the gas cars. This experiment shows how the model responds to different price settings of gas cars. A drop in price shows the manufactures wish to reduce their stocks and remove gas cars completely. The opposite is raising the prices, signifying that the gas car has become a collectors' item, a commodity that not everyone can have. Both are logical possibilities and both are modeled in the simulations.



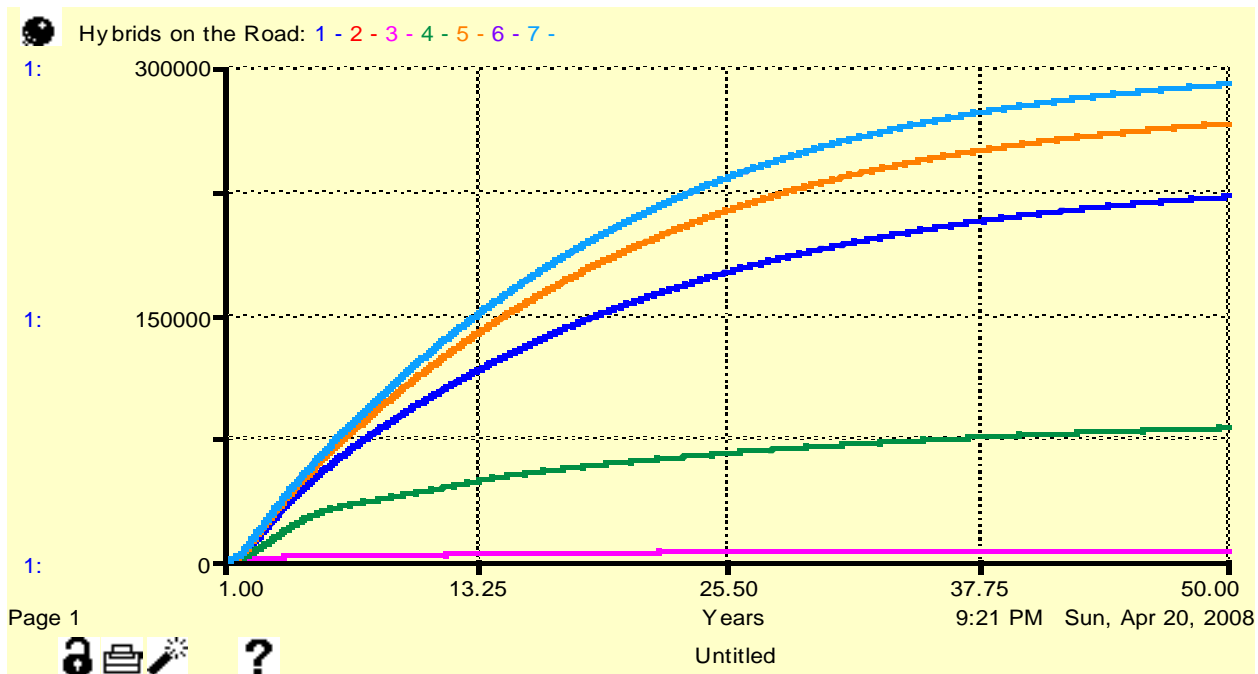


Figure 5-25 Hybrids on the Road - Experiment 11b

## 5.2. Overall Results

This section documents the outcomes of the system dynamics model developed to forecast the change in PHEV's in Massachusetts over a long period of time. It also reviews the impact of the consequent growth of PHEV's on the daily electric demand. More importantly, it will answer the primary question stated in the problem definition (section 1.1.).

The results of various modeling, research, and sensitivity exercises conducted during the course of this project show that PHEV's do take off and attain a sustainable value, as was the desired outcome. The impact on National Grid is minimal and the daily electric demand variation does not change significantly. On the finance side, the costs/expenses involved for launching PHEV's successfully (both upfront and long-term) are minimal. However, this will only occur if the right policies and procedures are followed by National Grid, the government, and the consumers.

Although the model has achieved its desired result and forecasts optimistic prospects for all those interested in PHEV's, it must be said that it does not incorporate certain factors that may significantly alter its behavior. For instance, battery technology limitations, such as potential hazards, decrease in capacity, or reduction in efficiency have not been taken into account. External factors such as the introduction of new technologies for replacing traditional gas cars may reduce the appeal for hybrids significantly, which will eventually hamper their growth. The next few pages shall present and explain the overall results shown by the model.

### 5.2.1. Hybrids on the Road vs. Cash

The time-variation of cash and hybrids on the road are two very important results that have been shown here. As can be observed, hybrids on the road increase with a slightly exponential trend in the first one or two years. This behavior eventually changes to a sustainable growth curve, where the number of PHEV's in Massachusetts attains a final value of around 120000 cars. The time-shape for Cash represents the variation in accumulation of annual profits over the given period of time. Since National Grid is a regulated industry, it should have zero economic profit annually, and the model structure for finances sector has been developed on the basis of this fact. Therefore, the time-shape for Cash should attain a sustainable growth, which implies that the goal of zero economic profit has been reached after some time. As can be observed, the cash available to National Grid indeed increases with a slowly decreasing trend in 50 years (approximate figures). Cash decreases initially for a small period of time since a certain amount of investment is offered from National Grid in the form of incentives for buying hybrids. The figures for cash are very large since an enormous amount of electricity is sold by National Grid every year.



Figure 5-26 Hybrids on the Road vs. Cash

### 5.2.2. Electricity Distribution

The time-shapes shown below are important indicators of how the introduction and charging of PHEV's will affect National Grid. It can be seen that only 3% of the total trough capacity is filled by the charging of PHEV's in 50 years, although a considerable number of such cars have been introduced into the system during this time (~135,000). The additional electric demand on National Grid during trough time-periods is also visible as the daily trough filled. This parameter attains an approximate value of 200 kVA in 50 years. Since the trough capacity is 20,000 kVA, it is evident that this filling of troughs by the charging of PHEV's shall not have a significant impact on the daily electric demand variation.

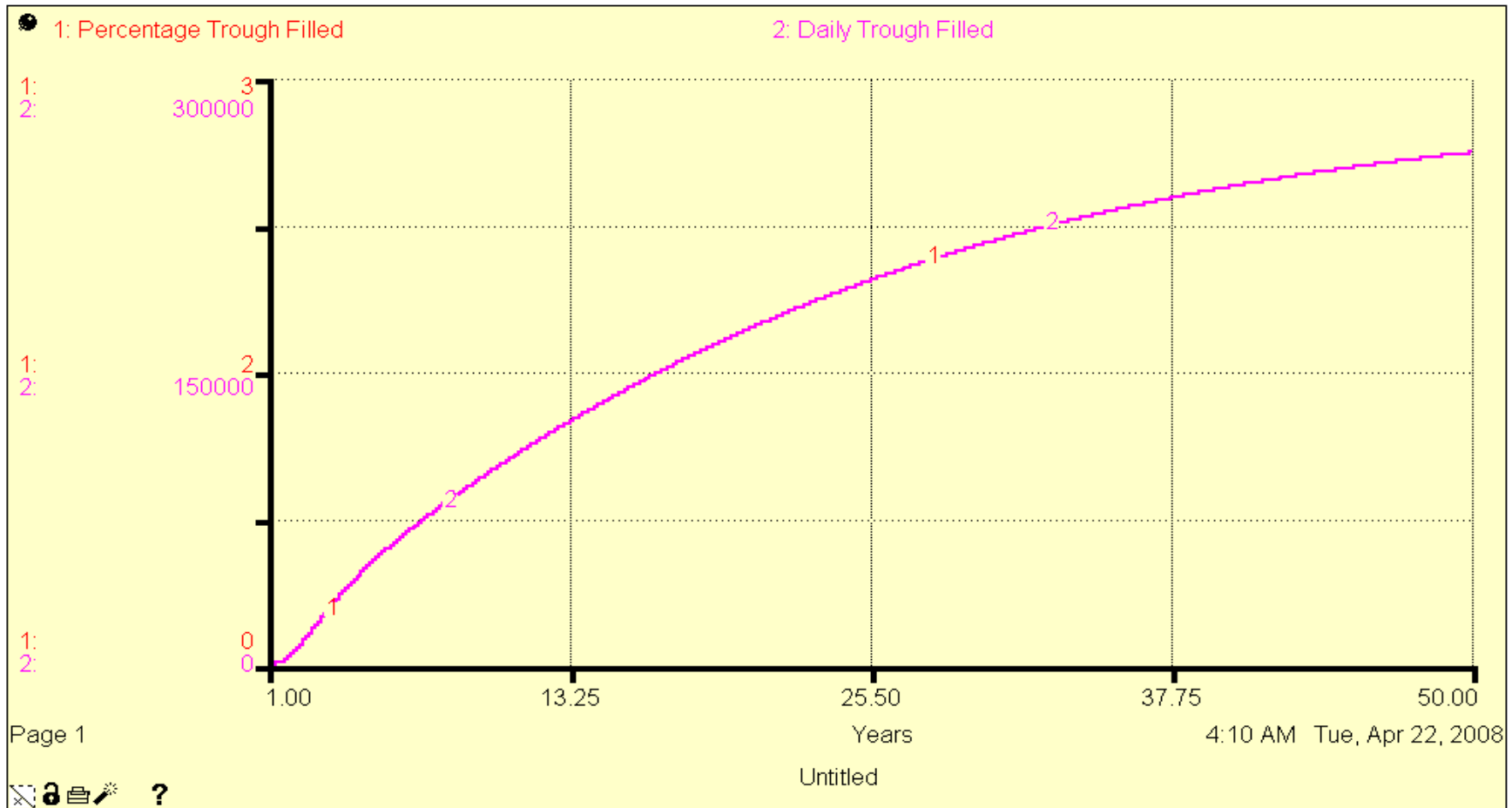


Figure 5-27 Percentage and Daily Trough Filled

### 5.2.3. Unit Energy Cost vs. Price

The time variation of unit energy cost and price can be seen in the figure below. Unit energy price is an important parameter that directly affects the amount billed to consumers for electricity. Since National Grid is a regulated industry, the difference between unit energy price and unit energy cost should ideally be nil. Although the values of each parameter do not change significantly, it can be observed that the difference between the two approaches zero towards the end of the modeling time period (50 years).

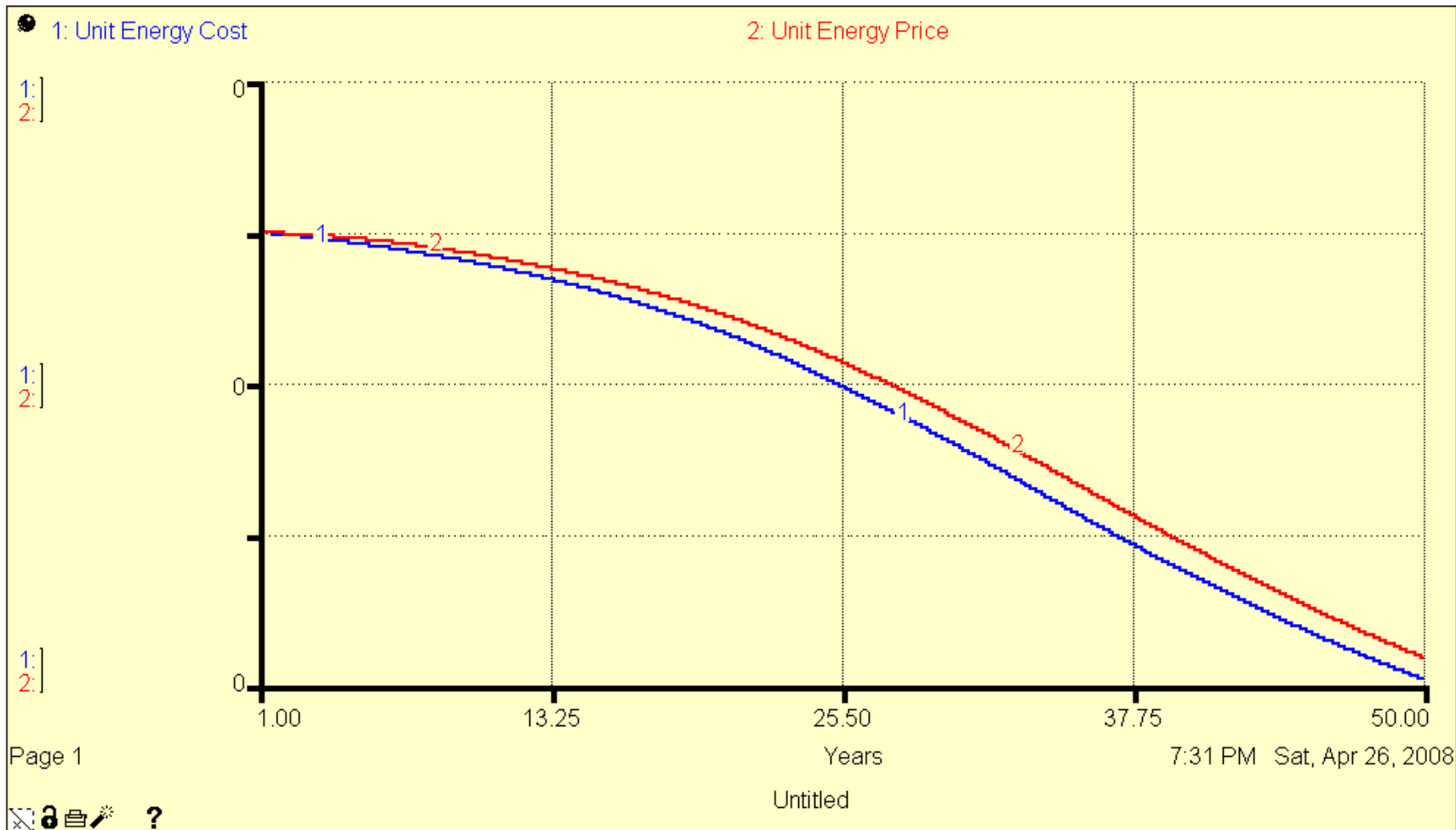


Figure 5-28 Energy Cost vs. Price

### 5.2.4. Unit Delivery Cost vs. Price

The time-shapes of unit delivery cost and price can be seen below. At first glance, they appear very similar to unit energy cost and price. However, since the sources that drive the fundamental costs of delivering and generating electricity are different, they have been defined differently in the model and hence have slightly different time-shapes. The desired difference (of zero) between cost and price is attained more slowly, since the unit delivery cost is directly related to annual electricity supplied by National Grid. As the electricity supplied increases very gradually, the cost of supplying (delivering) electricity decreases at a similar rate.



Figure 5-29 Delivery Cost vs. Price

### 5.2.5. National Grid Revenues and Expenses

The annual expense incurred and revenue generated are important variables that offer an insight into how the introduction of PHEV's into the system affects National Grid. It can be observed in the figure below that both revenues and expenses increase very rapidly for the first couple of years and then stabilize to very high values. Although at first glance it seems that revenues exceed expenses, a closer look at the scales will show that expenses are much lower than revenues at all times (except initially), which is the primary reason for the overall increase in cash according to the model structure. This is also observed by assessing the time shape of annual profits for National Grid over 50 years, as shown in the figure.

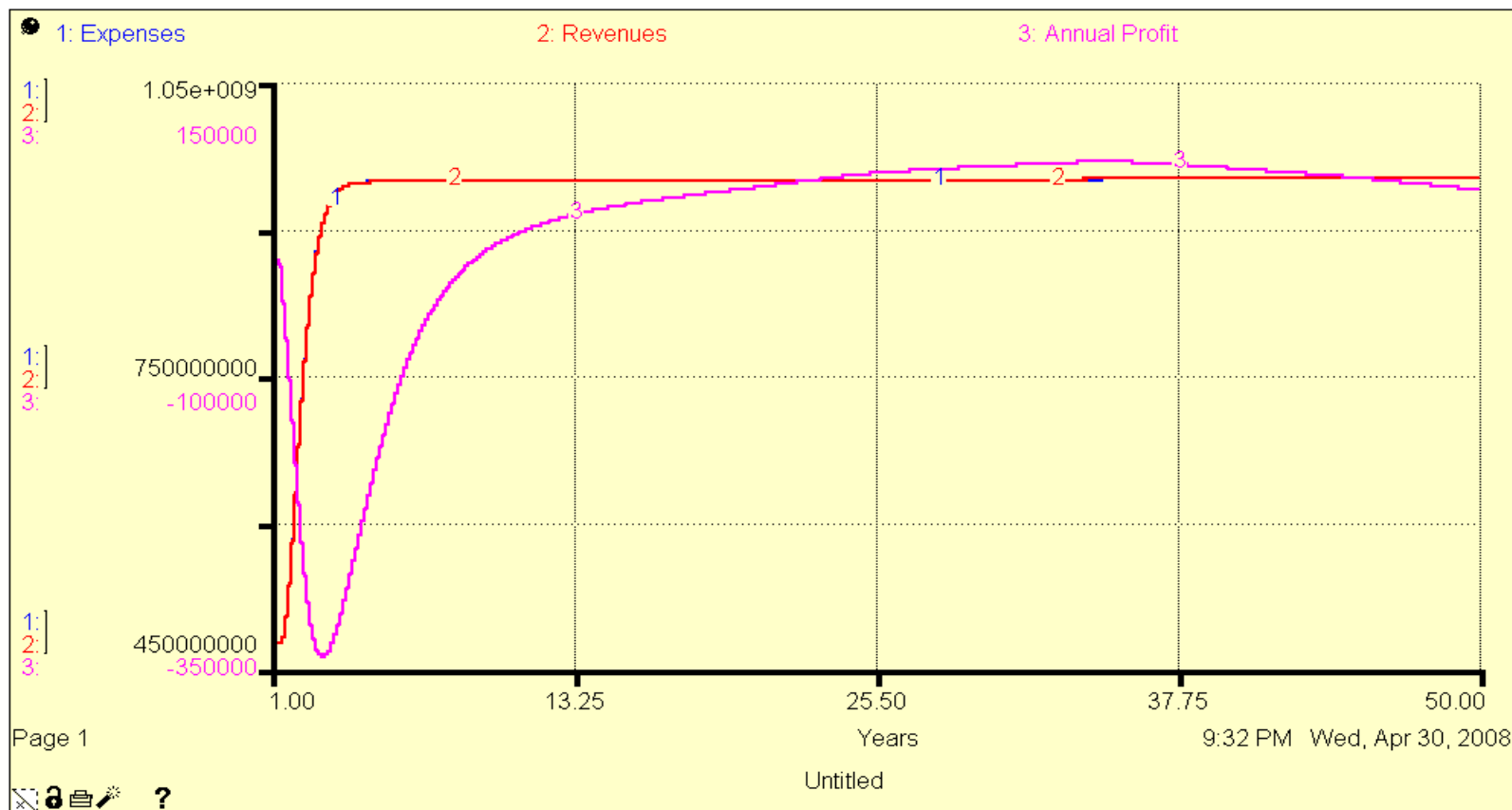


Figure 5-30 Revenues, Expenses and Annual Profit

### 5.2.6. Trough Usage and Upgrades

The time-shapes below outline the proposed upgrade policies/counter-measures that National Grid should adopt for maintaining a nominal trough capacity. An important part in this process is the development/upgrade of capacity for transformers and substations. These upgrades usually happen discreetly, which implies that after the nominal life of 170 years for a transformer/substation has been achieved, immediate measures are taken to replace it. However, the model structure has developed such upgrades as a continuous process because it is more efficient and cost effective for both decision makers in National Grid and consumers. The units for building rate are kVA/yr.



Figure 5-31 Trough Usage and Upgrades

### 5.2.7. Appeal for Hybrids

The appeal for hybrids is an important driving force in the growth of PHEV's, due to which the factors influencing are of considerable interest. The figure below shows time-variations of hybrid appeal as a function of operational cost, capital cost, and general popularity (diffusion effect). The variables 1,2, and 3 in the figure are all graphical functions. Operational Cost Appeal increases rapidly and attains a sustainable value of around 1 in a short period of 5 years (due to rising gas prices and lower hybrid operating costs with the development of technology). Capital Cost Appeal actually goes down since incentives provided by National Grid for reducing PHEV cost are very high initially and decrease to a very small value after some time. The diffusion effect of hybrids is a variable representing the increase in popularity of PHEV's by word-of-mouth propagation. The overall hybrid appeal as a product of all these factors predictably produces a sustainability curve with a maximum value of around 1.5 (cannot be observed due to scaling constraints).

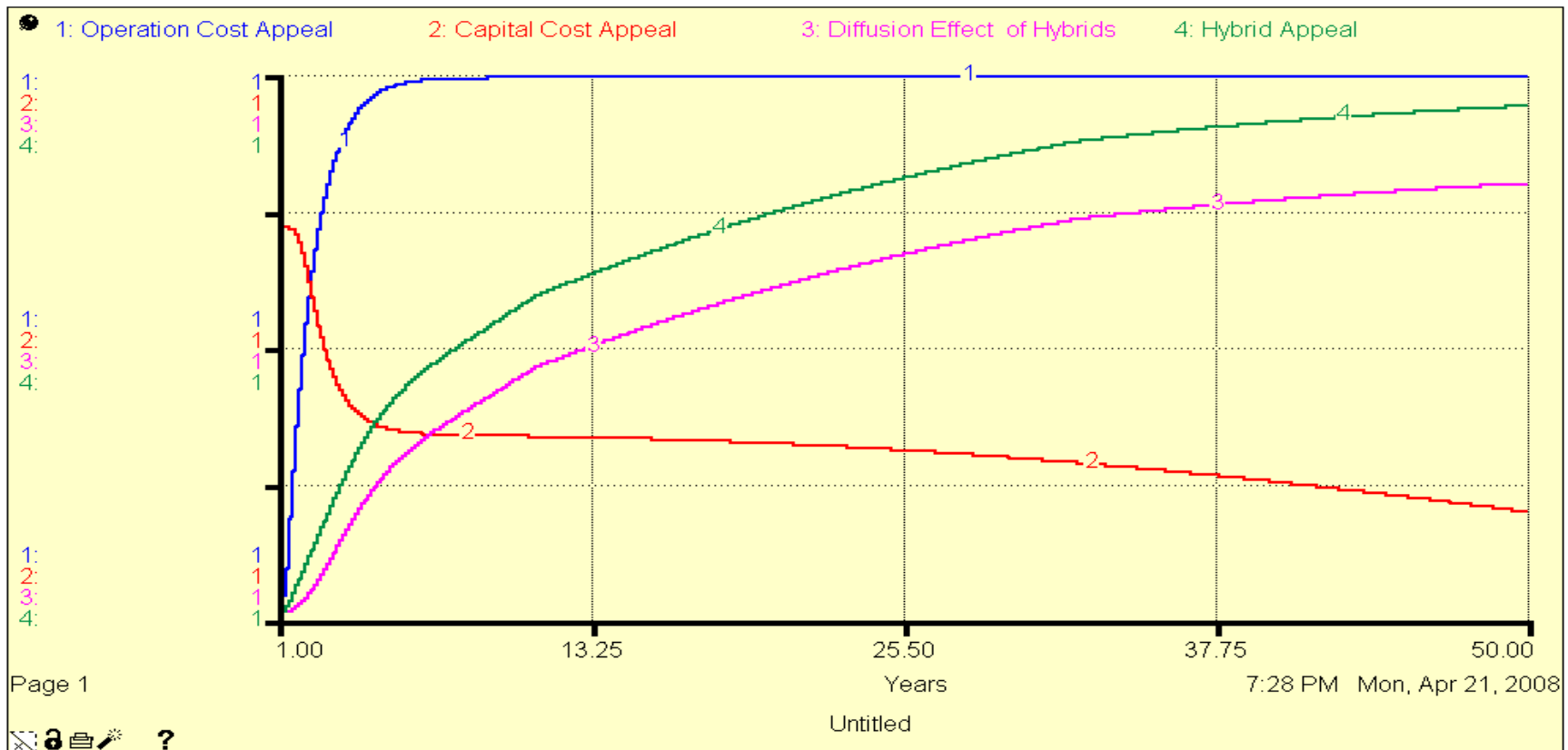


Figure 5-32 Appeal for Hybrids



### 5.2.8. PHEV Production and Sales

These variables drive the growth of PHEV's and hence form an important part of the discussion. The production and sales of hybrids almost match each other initially, since automobile dealers want to maintain a minimum inventory as well as meet the increasing demand for hybrids that occurs in the model. As the PHEVs on the road grow to very large values, the mismatch between production and sales is evident.

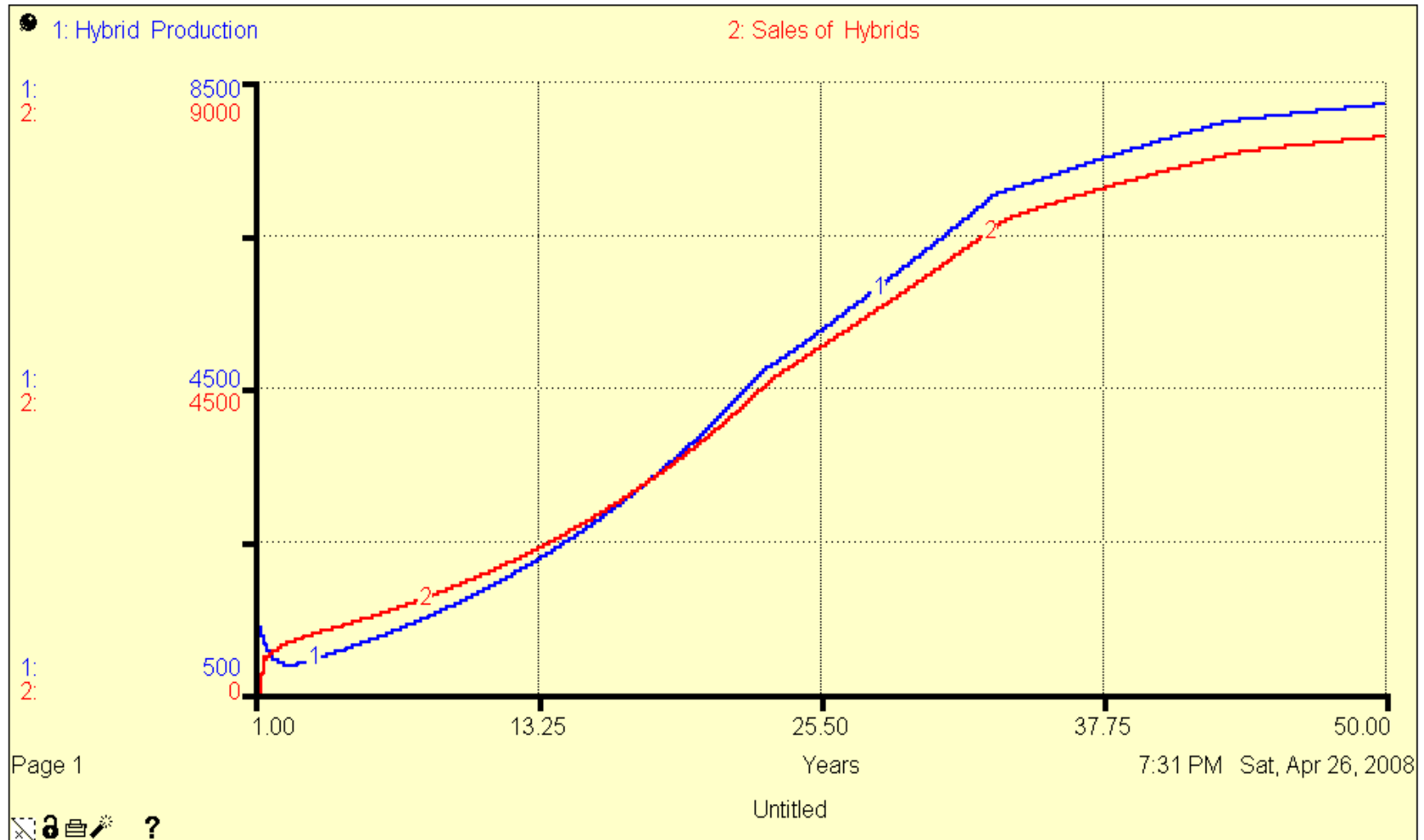


Figure 5-33 PHEV Production vs Sales

## 6. Possible Proposals

Based on the modeling and the assumptions associated with it, the project team has identified some areas where certain policies would be beneficial to both the introduction of Hybrid cars and National Grid. These are thus mentioned below:

1. It is recommended that charging for Hybrid cars should be done only during the times when the daily load is at its trough. This would translate to a charging period ranging from about 10 PM in the evening to 6AM in the morning. With PHEV's taking about 4 hours to charge, this could possibly mean splitting the charging into 2 cycles of 4 hrs each for different cars. The team has modeled this scenario and has come to the conclusion that the introduction of hybrid cars will not affect the filling of the troughs to a large extent. Hence, the transformers will not be subject to loads that would reduce its life and hence will not require frequent upgrades. Also, since the energy usually delivered during these trough periods comes from renewable sources, it is environmentally safe as well. This is extremely important as this could help address the question of whether PHEV's would actually increase emissions as a result of their charging (as the electricity being generated is generally perceived as being supplied by fossil fuel powered stations).

2. The team would also recommend that an ideal scenario of having all transformers inter-connected would be beneficial. Although this may not be practical and possible, having some sort of connection between transformers could be of value as well. The model has shown that if transformers were to be inter-connected, their lives would not be adversely affected with the coming of PHEV's. Since the load would be equally distributed, the addition on the troughs would be minimal and hence the substations will continue to function exactly the way they have been. This means that with no extra cost or no physical changes, the load from hybrid cars can be easily handled to provide benefit to all.

Although recommendations can be ideal in nature and not completely capable of being observed in practice, they are always a starting point to look at places where changes can be made in order to provide benefit to all. Thus, the team feels that the above mentioned proposals are of extreme importance and could be decisive in the future of PHEV's.

## 7. Conclusion

Through the modeling done in this project, the authors have obtained a much greater understanding of the real-world situation and of the factors affecting the advent of plug-in hybrids cars on the electricity distribution section and on National Grid as a whole. To sum it up, it has been seen that hybrid cars will be successful and manage to attain a significant number at which they settle. It has also been seen that National Grid is working more or less as regulated industry as the changes in cash remain relatively small. Also, the effect on the electricity distribution sector and the change in life of the consequent transformers is minimal; this may be due to the underlying assumptions which have been mentioned earlier in section 3.2.

Although the outcomes have been many and extremely insightful, a lot of further expertise can be achieved with this current frame-work as a base. The authors have stated various assumptions all throughout this document and are at a position where they can be challenged in order to achieve more insightful results. In order to be more specific, some insight on the questions to be addressed in future work will now be provided.

The team hopes to provide further insight into the electricity distribution sector by questioning the current assumption of having all transformers to be interconnected. The team wishes to address how exactly a substation could be affected if it serves primarily residential loads.

Also, the team aims at analyzing the environmental impact related to the coming of hybrid cars. Currently, there is a lot of skepticism in regards to where the electricity for the batteries of PHEV's would come from and hence whether the reduction of gasoline cars and the coming of hybrids cars would actually reduce harmful emissions or not.

The team will also try to look at the possible impact of PHEV's on society. The questions that will be addressed will possibly include how the entire auto-industry will be affected; possible impacts on the economy if PHEV's can create new jobs or take away current jobs. Lastly, some more insight on the other alternative car technologies and how they could affect PHEV's and the entire future of the auto industry as a whole could be provided.

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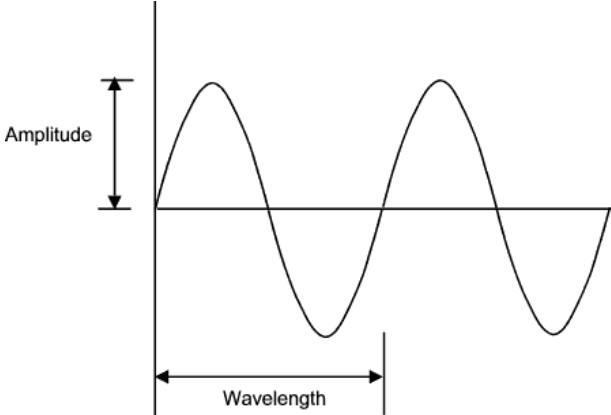
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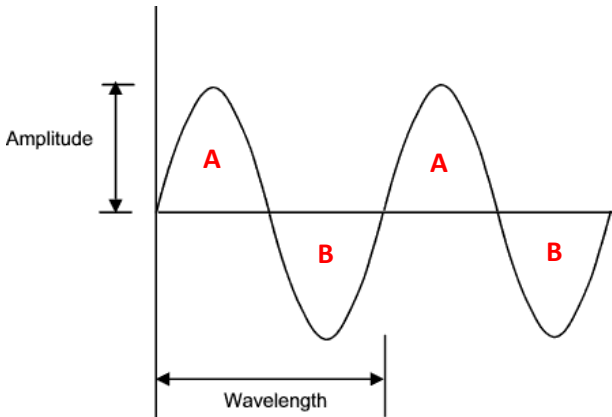
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# 10. Appendices

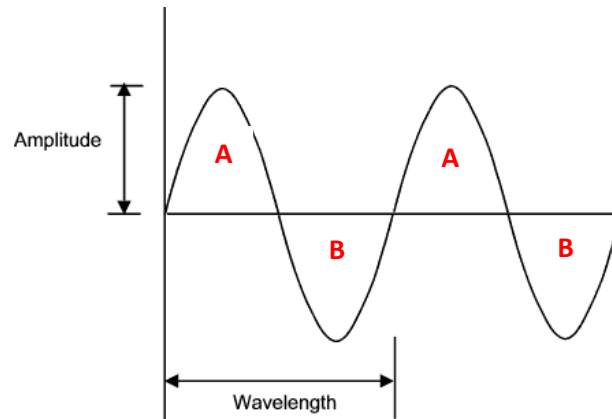
## Appendix A. Glossary of technical terms

<p>1. <b>Amplitude:</b> The difference between the peak and normal value of a sinusoidal function.</p> 
<p>2. <b>CAES:</b> Compressed Air Energy Storage, or CAES, is an emerging alternative technology for propulsion in vehicles that may replace the current system used in traditional internal combustion engines. Briefly, CAES utilizes the potential energy of stored compressed air for driving pistons in a car engine.</p>
<p>3. <b>Capacity:</b> Specifically for this document, capacity refers to the nominal electric supply that can be provided by transformers at the distribution side.</p>
<p>4. <b>Carbon footprint:</b> The amount of carbon dioxide that an individual, society, or organization adds to the atmosphere, consequently contributing to global warming.</p>
<p>5. <b>Carbon neutral:</b> A device, product, or utility that does not add carbon dioxide to the atmosphere due to its use or adequate disposal.</p>
<p>6. <b>Casual Loops:</b> Feedback loops that form the basic structure of a dynamic hypothesis and outline the dynamic relationship between variables in a system</p>
<p>7. <b>Ceteris Paribus:</b> A Latin term meaning 'keeping all other things constant'</p>
<p>8. <b>Demand Profile:</b> The time variation of electricity demanded by consumers from the local grid. For this document, it is an hour-by-hour variation of electric demand over a period of 24 hours.</p>
<p>9. <b>Dynamic hypothesis:</b> A diagram of the various relationships between major system variables that facilitates a better understanding of dynamics of the system under study.</p>
<p>10. <b>Efficiency:</b> The ratio of power or energy that can be delivered from a device to the power/energy required to operate it.</p>
<p>11. <b>FCV:</b> Fuel Cell Vehicle, or FCV for short, is an innovative technology intended to replace traditional gasoline vehicles that utilizes electricity generated from the combination of hydrogen and oxygen for</p>

providing kinetic energy.
<b>12. Feedback Loops:</b> <i>Please see 6. Causal Loops</i>
<b>13. Flows:</b> They are periodic or regular inputs/outputs to and from stocks that consequently alter their behavior
<b>14. Forecast model:</b> A system dynamics model that predicts the change in major system variables over a given period of time
<b>15. ICE:</b> Internal Combustion Engine, or ICE for short, is the traditional method of driving vehicles that has remained popular for over 8 decades.
<b>16. Incentives:</b> For this project, incentives refer to cash discounts or rebates by the federal/state government and National Grid to encourage the growth of PHEVs
<b>17. System Dynamics Model:</b> A structure comprising stocks, flows, and parameters that is used to study the change in major system variables. The model itself is usually a forecast model that is used to predict possible changes in a system after a long period of time (such as 100 years)
<p><b>18. Peak:</b> The portion of a sinusoidal function that is above its 'normal' (average) value. For example, for a curve <math>f(t) = (\cos(t) + 10)</math>, the normal value will be 10. Peaks are denoted by A in the illustration below.</p> 
<b>19. PHEV:</b> Plug-in Hybrid Electric Vehicles, or PHEVs for short as they have been used throughout this document, are modern vehicles which utilize on-site electrical energy storage in batteries to increase their efficiency and function in harmony with traditional International Combustion Engines
<b>20. Policies:</b> Rules and regulations set down by the government, National Grid, or students working for this project. For this report specifically, policies refer to additional functionalities in the system dynamics model that are added to facilitate the growth of PHEVs
<b>21. Reference mode:</b> A set of time variation graphs of the major system variable that establish its expected behavior.
<b>22. Regulated Industry:</b> An organization that has limited net profits and aims to achieve zero economic

<p>profit. The federal or state government(s) monitor the organization's activities to ensure that its goal of minimal profit is obtained. Such organizations usually belong to the services/utilities sector (such as National Grid and NStar)</p>
<p><b>23. Sector:</b> An area of a system dynamics model that deals with a specific portion of the system under study.</p>
<p><b>24. Sensitivity analysis:</b> A method of conducting experiments with a system dynamics model to observe the effect of altering various parameters on the major system variable(s).</p>
<p><b>25. Simulation:</b> A computer based run of a dynamic system that facilitates a study of the change in major system variables as well as sensitivity analysis</p>
<p><b>26. Stocks:</b> A reservoir of some quantity (such as cars, profits) that accumulates every year. Stocks can be used to show the growth in major system variables over a long period of time.</p>
<p><b>27. Substation:</b> A venue owned and maintained by the local electric grid that contains transformers used for stepping down voltage before distributing it to various customers</p>
<p><b>28. Sustainability:</b> The ability of a system to function under various conditions and circumstances without any significant change. For this report, sustainability is the desired reference mode.</p>
<p><b>29. System dynamics:</b> System dynamics is an approach to understanding the behavior of complex systems over time. It deals with internal feedback loops and time delays that affect the behavior of the entire system.</p>
<p><b>30. System variables:</b> Major items in a system that may change dynamically with time or influence other changes.</p>
<p><b>31. Tax Credit:</b> Possible discounts/incentives for consumers to go green and/or purchase PHEVs</p>
<p><b>32. Tax Deduction:</b> Countermeasures that the federal/state governments have initiated to curb the widespread usage of low mileage gasoline cars.</p>
<p><b>33. Tax Exemption:</b> An exemption from various state/federal taxes that offers an incentive for consumers to purchase PHEVs and generally reduce their carbon footprint</p>

**34. Trough:** The portion of a sinusoidal function that is below its normal value. Troughs are denoted by B in the illustration below.



**35. VOCs:** Volatile Organic Compounds, or VOCs in short, are chemicals released during the combustion of gasoline. They form a part of the exhaust gases from a traditional ICE car, and are believed to be harmful to the environment

## Appendix B. Background Research

### B.1 Air cars in India

Tata has come up with a venture with MDI (Motor Development International), to launch air cars in India. Since electricity would be used to compress the air, the cars essentially run on electricity - so they are almost as clean as electric cars. Where they score above electric cars is that the energy is not stored in batteries but in a rather simple tank, hence they are cheaper and have a greater range.

The core of the compressed air engine would be a single-piston engine powered by the expansion of compressed air. MDI's single fuel engines will run purely on compressed air and cars with these engines will top out at 35 mph. The dual fuel engine cars will have the capability to switch to a combustible fuel at speeds above 35 mph, and when on this mode the compressed air tank gets refueled too.

The compressed air can be refilled at special facilities at petrol stations in quick time (2-3 minutes), or in 3-4 hours plugging in the car's electric compressor to the mains. So the car will essentially run on electric power converted into compressed air. Once filled up, the car should run for 150 to 230 miles. Each commercial refill should cost about \$3. Recharging from the mains at home however should cost far less. The car is expected to cost about \$7500.

### B.2 The Fuel Cell Possibility

A **fuel cell** is an electrochemical energy conversion device. It produces electricity from various external quantities of fuel (on the anode side) and oxidant (on the cathode side). These react in the presence of an electrolyte. Fuel cells can operate virtually continuously as long as the necessary flows are maintained.

Fuel cells are different from batteries in that they consume reactant, which must be replenished, while batteries store electrical energy chemically in a closed system. Additionally, while the electrodes within a battery react and change as a battery is charged or discharged, a fuel cell's electrodes are catalytic and relatively stable.

Many combinations of fuel and oxidant are possible. A hydrogen cell uses hydrogen as fuel and oxygen as oxidant. Other fuels include hydrocarbons and alcohols. Other oxidants include air, chlorine and chlorine dioxide.

The Department of Energy's Technical Plan for Fuel Cells states that the air compressor technologies currently available are not suitable for vehicle use, which makes designing hydrogen fuel delivery system problematic.

In order for PEMFC vehicles to become a viable alternative for consumers, there must be a hydrogen generation and delivery infrastructure. This infrastructure might include pipelines, truck transport, fueling stations and hydrogen generation plants. The DOE hopes that development of a marketable vehicle model will drive the development of an infrastructure to support it.

Three hundred miles is a conventional driving range (the distance one can drive in a car with a full tank of gas). In order to create a comparable result with a fuel cell vehicle, researchers must overcome hydrogen storage considerations, vehicle weight and volume, cost, and safety.

There is also safety concerns related to fuel cell use. Legislators will have to create new processes for first responders to follow when they must handle an incident involving a fuel cell vehicle or generator. Engineers will have to design safe, reliable hydrogen delivery systems.

### **B.3 Battery research at MIT**

Anne Trafton, News Office

February 16, 2006

Researchers at MIT have developed a new type of lithium battery that could become a cheaper alternative to the batteries that now power hybrid electric cars.

Until now, lithium batteries have not had the rapid charging capability or safety level needed for use in cars. Hybrid cars now run on nickel metal hydride batteries, which power an electric motor and can rapidly recharge while the car is decelerating or standing still.

But lithium nickel manganese oxide, described in a paper to be published in Science on Feb. 17, could revolutionize the hybrid car industry.

The new material is more stable (and thus safer) than lithium cobalt oxide batteries, which are used to power small electronic devices like cell phones, laptop computers, rechargeable personal digital assistants (PDAs) and such medical devices as pacemakers.

The small safety risk posed by lithium cobalt oxide is manageable in small devices but makes the material not viable for the larger batteries needed to run hybrid cars, Ceder said. Cobalt is also fairly expensive, he said.

The MIT team's new lithium battery contains manganese and nickel, which are cheaper than cobalt. Scientists already knew that lithium nickel manganese oxide could store a lot of energy, but the material took too long to charge to be commercially useful. The MIT researchers set out to modify the material's structure to make it capable of charging and discharging more quickly.

Lithium nickel manganese oxide consists of layers of metal (nickel and manganese) separated from lithium layers by oxygen. The major problem with the compound was that the crystalline structure was too "disordered," meaning that the nickel and lithium were drawn to each other, interfering with the flow of lithium ions and slowing down the charging rate.

Lithium ions carry the battery's charge, so to maximize the speed at which the battery can charge and discharge, the researchers designed and synthesized a material with a very ordered crystalline structure, allowing lithium ions to freely flow between the metal layers.

A battery made from the new material can charge or discharge in about 10 minutes -- about 10 times faster than the unmodified lithium nickel manganese oxide. That brings it much closer to the timeframe needed for hybrid car batteries.

#### **B.4 Incentives for going green**

Renewable Power Production Tax Credit: Recently extended through 2004, residential and business generators of renewable power may be entitled to a credit of 1.5 cents per kWh of energy produced by qualified sources, including new wind, closed-loop biomass, and poultry waste facilities.

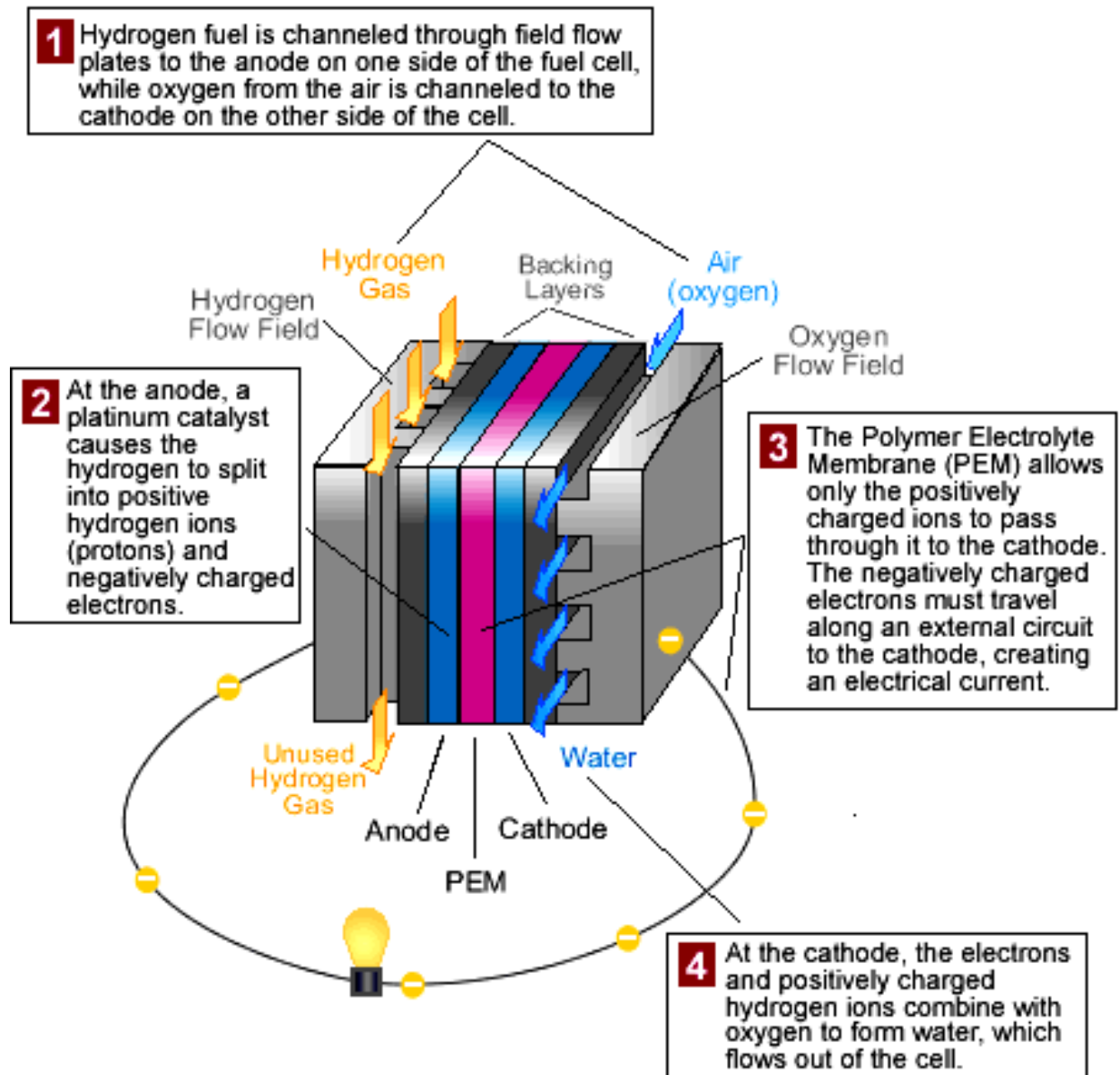
The U.S. Department of Energy (DOE) today announced that DOE will invest up to \$13.7 million, over three years (Fiscal Years 2008 – 2010), for 11 university-led projects that will focus on developing advanced solar photovoltaic (PV) technology manufacturing processes and products. These projects are integral to President Bush's Solar America Initiative, which aims to make solar energy cost-competitive with conventional forms of electricity by 2015. Increasing the use of solar energy is also critical to diversifying the nation's energy sources in an effort to reduce greenhouse gas emissions and dependence on foreign oil. Combined with a minimum university and industry cost share of 20%, up to \$17.4 million will be invested in these projects.

**DOE to Provide Nearly \$20 Million to Further Development of Advanced Batteries for Plug-in Hybrid Electric Vehicles-** U.S. Department of Energy (DOE) Assistant Secretary for Electricity Delivery and Energy Reliability Kevin M. Kolevar today announced DOE will invest nearly \$20 million in plug-in hybrid vehicle (PHEV) research. Five projects have been selected for negotiation of awards under DOE's collaboration with the United States Advanced Battery Consortium (USABC) for \$17.2 million in DOE funding for PHEV battery development projects and; DOE will provide nearly \$2 million to the University of Michigan (U-M) to spearhead a study exploring the future of PHEVs.

**Out of this: A123Systems of Watertown, MA** – selected for an award of up to \$6.25 million from DOE (total DOE/industry cost share: \$12.5 million) over three years for a project to develop batteries based on nanophase iron-phosphate chemistry for 10- and 40-mile range PHEVs.

## Appendix C. Figures and Tables

### C.1 How fuel cells work

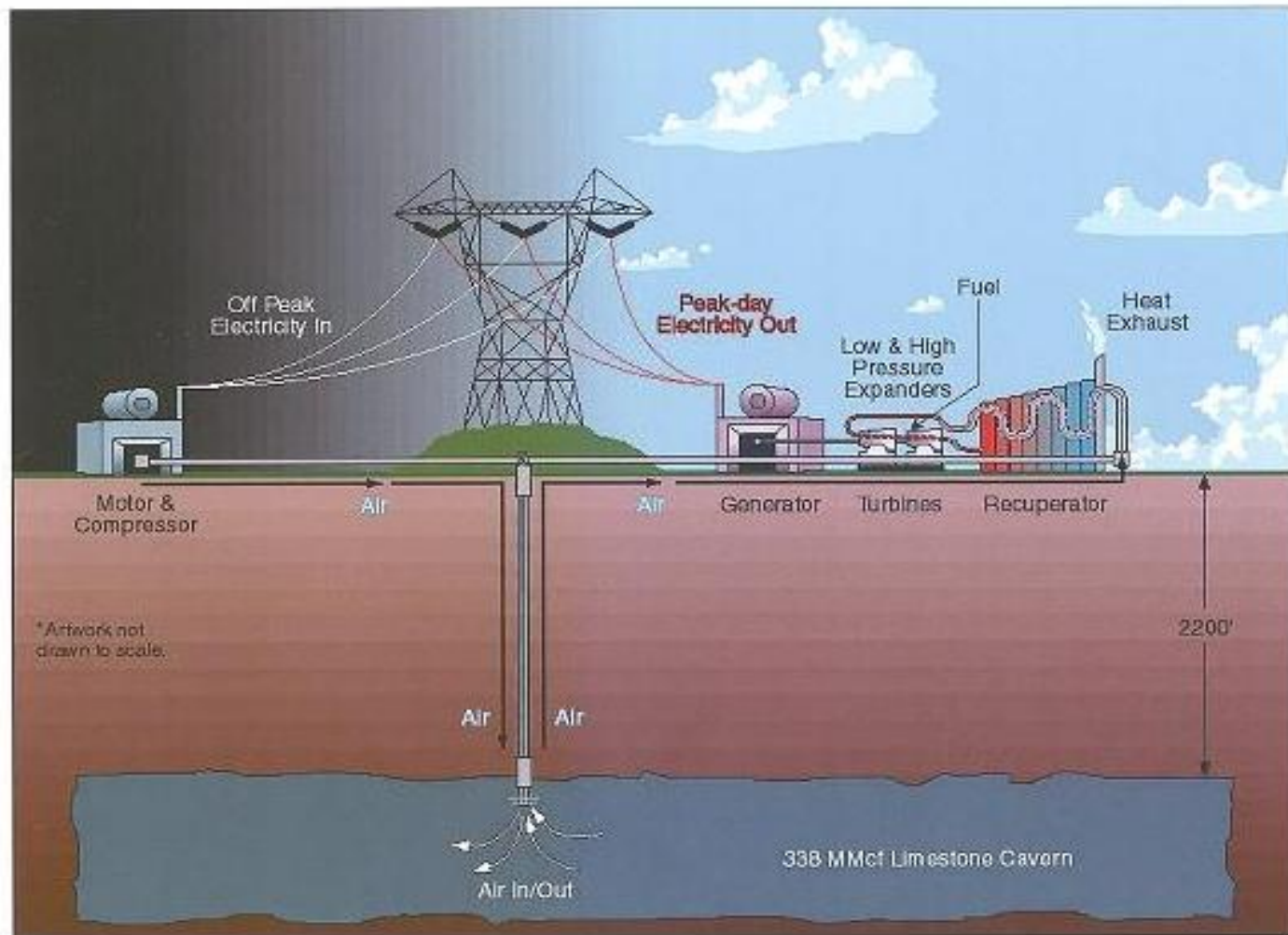




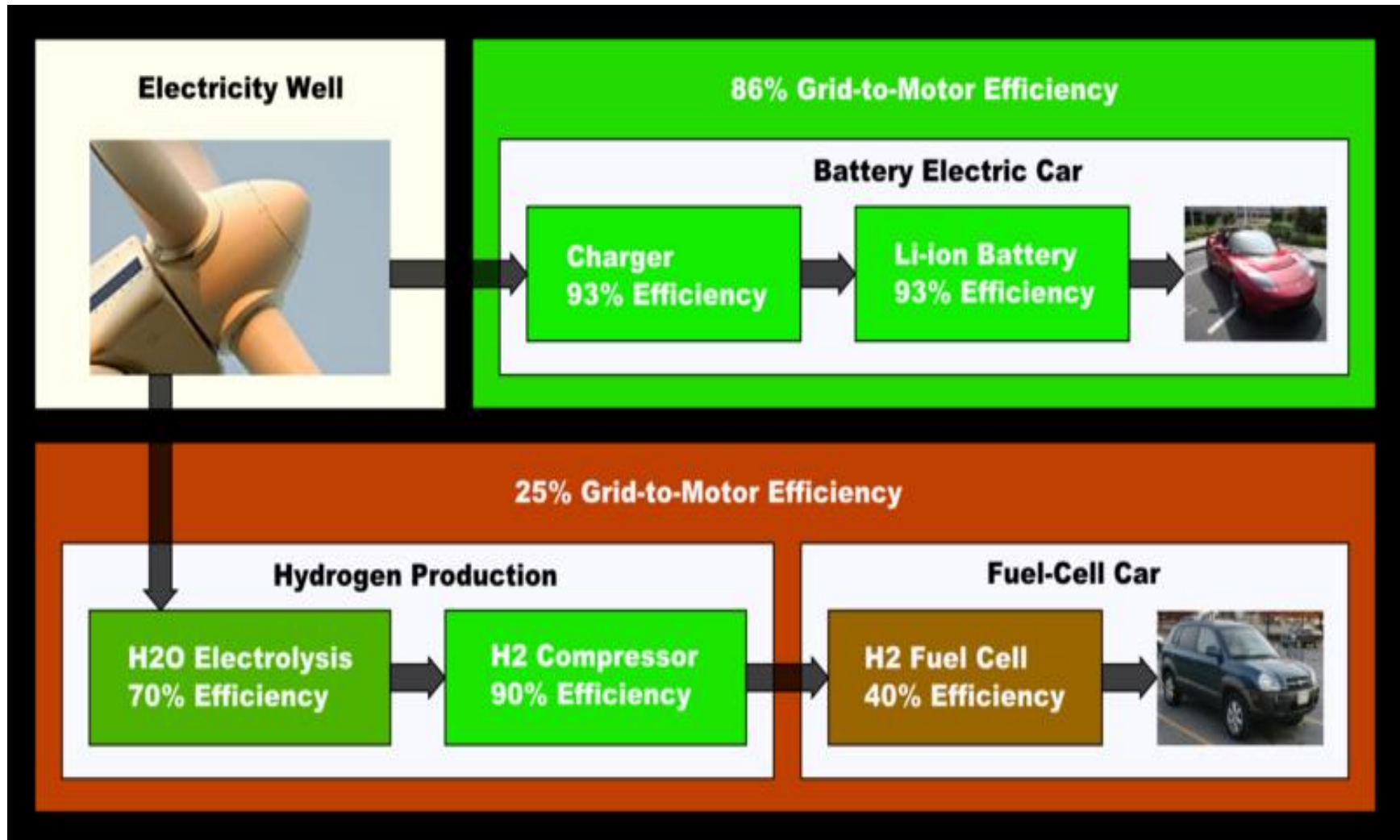
C.2 CAES usage at the large-scale

# Norton Energy Storage

## The CAES Cycle



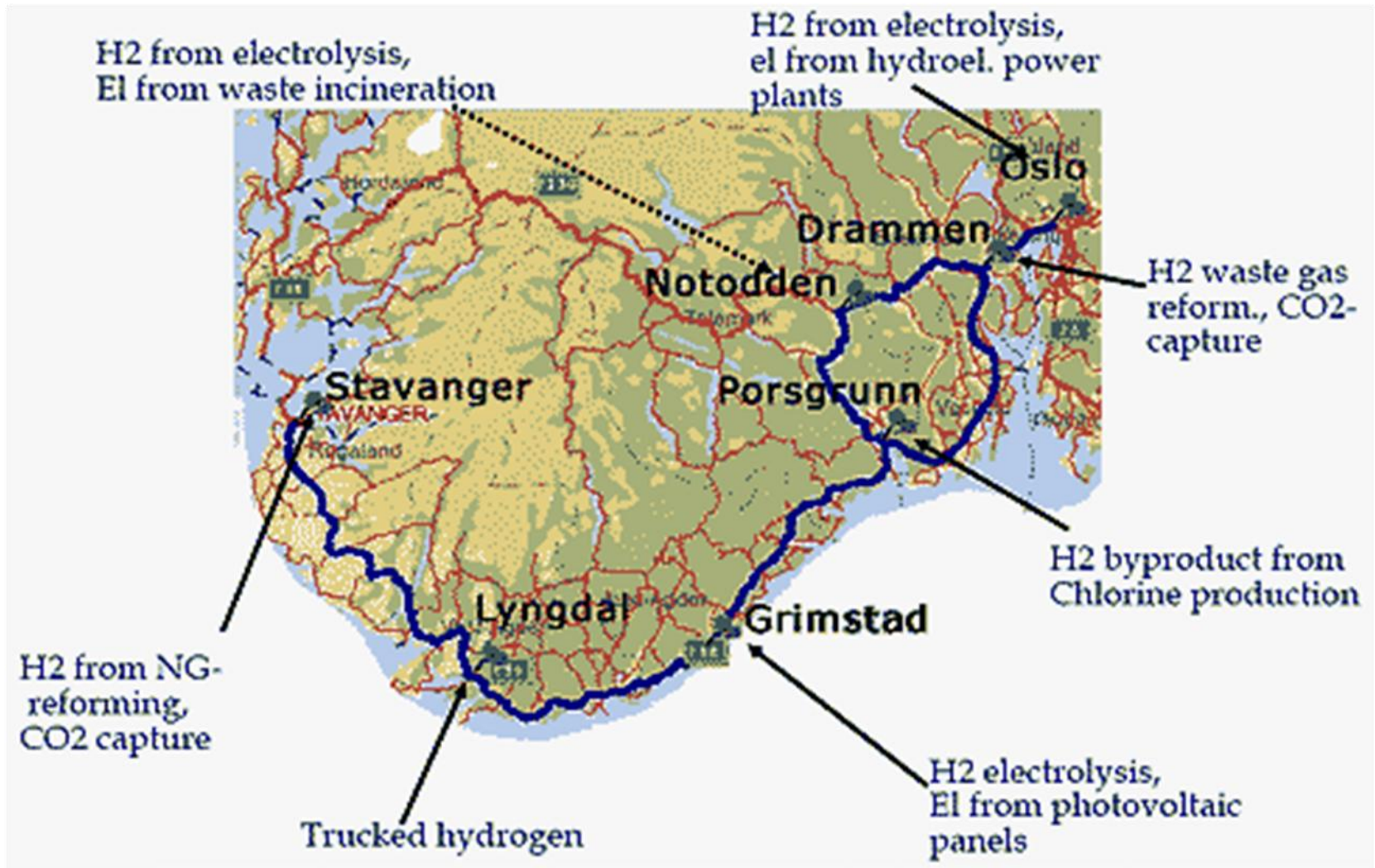
### C.3 Energy efficiency comparison of Electric and Fuel Cell vehicles



#### C.4 Advantages and Disadvantages of Compressed Air Propulsion Technology

Advantages	Disadvantages
<ul style="list-style-type: none"> <li>• The costs involved to compress the air to be used in a vehicle are inferior to the costs involved with a normal combustion engine.</li> <li>• Air is abundant, economical, transportable, storable and, most importantly, nonpolluting.</li> <li>• The technology involved with compressed air reduces the production costs of vehicles with 20% because it is not necessary to assemble a refrigeration system, a fuel tank, spark plugs or silencers.</li> <li>• Air itself is not flammable</li> <li>• The mechanical design of the motor is simple and robust</li> <li>• It does not suffer from corrosion damage resulting from the battery.</li> <li>• Less manufacturing and maintenance costs.</li> <li>• The tanks used in an air compressed motor can be discarded or recycled with less contamination than batteries</li> <li>• The tanks used in a compressed air motor have a longer lifespan in comparison with batteries, which, after a while suffer from a reduction in performance.</li> </ul>	<ul style="list-style-type: none"> <li>• Limited range due to available tank technology. The air engine suffers from similar problems to hydrogen vehicles in this regard.</li> <li>• Using energy to compress air is less efficient than charging a battery with that same energy.</li> <li>• Less efficient than electric motors.</li> <li>• While the air engine reduces greenhouse gas emissions from the vehicle, the energy used to compress the air may not come from clean sources.</li> <li>• Overall efficiency is approximately one third of a comparable electric car.</li> </ul>

C.5 Proposals for Norwegian HyNor solution



## C.6 Characteristics comparison – PHEV conversion kits for Toyota Prius

[hide] Comparison table: [PHEV](#) conversion and kit options for the [Toyota Prius](#)

Organization :Location Websites (Products)	Conv. service <a href="#">[7]</a>	Conv. kit <a href="#">[7]</a>	Status <a href="#">[8]</a>	# done so far <a href="#">[9]</a>	EV range [mi] <a href="#">[1]</a>	PHEV range [mi] <a href="#">[2]</a>	AC power <a href="#">[10]</a>	Charge time [hours] <a href="#">[4]</a>	Safety <a href="#">[3]</a>	Added weight [kg] <a href="#">[11]</a>	Spare Tire <a href="#">[6]</a>	Cost [US\$] <a href="#">[12]</a>	Type <a href="#">[9]</a>	Pack energy [KWh] <a href="#">[5]</a>	DOD energy [KWh] <a href="#">[5]</a>	Bat type <a href="#">[13]</a>
<a href="#">PriusPlus</a> :CA <a href="#">[10]</a> <a href="#">CalCars</a> (Pb  NiMH)	No	Yes	Dev Doc	5 <a href="#">[11]</a>	10-12  20-25	20+  40+	100 to 240 Vac	4+  5 <a href="#">[4]</a>	Flame Spill proof	130  100	Opt	\$3- \$9K +Labor <a href="#">[12]</a>	Hyb Con CV	4.8  6.5	2.4-3.8  +0.3 stock  5	PbA (Ni, Li) <a href="#">[13]</a>
<a href="#">PiPrius</a> :WA <a href="#">Manzanita</a> <a href="#">Micro</a> , <a href="#">PiPrius</a> , <a href="#">AVI</a> , <a href="#">Green Car Co.</a>	No	Yes	Dev Doc	4 <a href="#">[14]</a>	10	20-30	90 to 300 Vac Vdc	0.4-3+ <a href="#">[15]</a> <a href="#">[4]</a>	Flame Spill proof	150	no	\$10K +Labor <a href="#">[16]</a>	Hyb DC CV <a href="#">[17]</a>	4.7	4+0.3 stock	PbA (Ni, Li) <a href="#">[18]</a>
<a href="#">EnergyCS</a> :CA <a href="#">EnergyCS</a>	Yes	No	Prod	11	30	50	120 Vac	9.0	Flame Spill proof	83	no	\$40K	New	9 <a href="#">[19]</a>	8	Li <a href="#">[20]</a>
<a href="#">Amberjac</a> :UK <a href="#">Amberjac</a> EnergyCS partner <a href="#">[21]</a>	Yes	No	Prod	7	30	60-70	110 to 230 Vac	9.0	Flame Spill proof	83	yes	\$40K	New	9 <a href="#">[22]</a>	8	Li <a href="#">[23]</a>
<a href="#">EDrive</a> :CA <a href="#">EDrive</a>	?	?	Dev	0	32?	60?	100 to	9.0	via cell sep	?	yes	?	New	9.5	8.5?	Li

<u>Systems</u>												240 Vac	[24]	[25]		
<u>Hymotion</u> :ON Canada <u>Hymotion /A123</u> (PHEV-L5)	Yes, fleets	No	Prod	18	15 [26]	100 to 240 Vac	5.5 / 4.0	Spill proof	72	no	\$10K [27]	Hyb	5.0	4+0.3 stock	Li [28]	
<u>Hybrids-Plus</u> :CO <u>Hybrids-Plus (Prius-30</u> <u>Prius-15)</u>	Yes	Future	Prod	3	30	50	9.0	Flame Spill proof	81	yes	\$32K	New	9.0	8	Li [30]	
					15	25	5.5		21		\$24K [29]		4.5	4		
					8	16	2		40		\$8K		2.1	1.7		
<u>Plug-In</u> <u>Conversions</u> :CA <u>Plug-In</u> <u>Conversions</u>	Yes	Yes	Dev Doc	3	16	32	100 to 240 Vac	4	Flame Spill proof	80	Opt	\$24K	Hyb Con CV	4.3	3.5	NiMH [32]
					24	48		6		120		\$15K [31]		6.5	5.2	
<u>OEMtek</u> :CA <u>OEMtek</u>	Yes	No	Dev	?	30	50	100/240 Vac	4/6	Flameproof	95	Yes	\$12K	Hyb	9	8	Li

## Appendix D. National Grid Class Tariffs

### D.1 R-1 Residential Regular

#### MASSACHUSETTS ELECTRIC COMPANY

Residential Regular R-1  
M.D.T.E. No.1105

Effective  
March 1, 2007

Adjusted By:

Transition Cost Adjustment	March 1, 2007
Transmission Service Cost Adjustment	March 1, 2007
Default Service Adjustment	March 1, 2007
Residential Assistance Adjustment	March 1, 2007
Default Service Cost Reclassification Adjustment	November 1, 2007

#### Monthly Charge as Adjusted

#### Rates for Retail Delivery Service

<u>Customer Charge</u>	\$6.10	
<u>Distribution Charge per kWh (1)</u>	2.520¢	
<u>Transmission Charge per kWh</u>	1.238¢	
<u>Transition Charge per kWh</u>	0.390¢	
<u>Demand Side Management Charge per kWh</u>	0.250¢	effective January 1, 2003
<u>Renewables Charge per kWh</u>	0.050¢	effective January 1, 2003

#### Rates for Supplier Service

<u>Default Service Charge per kWh</u>	per Tariff for Default Service
---------------------------------------	--------------------------------

#### Interruptible Credits

IC-1	\$5.78
IC-2	\$7.88
IC-3 (billing months of July, Aug., Sept., Oct. only)	\$6.00
IC-4 (billing months of July, Aug., Sept., Oct. only)	\$6.50

#### Minimum Charge

The monthly Customer Charge.

Other Rate Clauses apply as usual.

(1) Includes Default Service Adjustment Factor of 0.003¢ per kWh, Residential Assistance Adjustment Factor of 0.014¢ per kWh, Default Service Cost Reclassification Adjustment Factor of (0.127¢) per kWh.

## D.2 R-2 Residential Low Income

### MASSACHUSETTS ELECTRIC COMPANY

Residential Low Income R-2  
M.D.T.E. No. 1106

Effective  
March 1, 2007

Adjusted By:

Transition Cost Adjustment	March 1, 2007
Transmission Service Cost Adjustment	March 1, 2007
Default Service Adjustment	March 1, 2007
Residential Assistance Adjustment	March 1, 2007
Default Service Cost Reclassification Adjustment	November 1, 2007

#### Monthly Charge as Adjusted

#### Rates for Retail Delivery Service

<u>Customer Charge</u>	\$3.96	
<u>Distribution Charge per kWh (1)</u>	0.376¢	
<u>Under Individual Customer Protection Provision:</u>		
<u>Customer Charge</u>	\$0.91	
<u>Distribution Charge per kWh (1)</u>	0.498¢	
<u>Transmission Charge per kWh</u>	1.238¢	
<u>Transition Charge per kWh</u>	0.361¢	
<u>Demand Side Management Charge per kWh</u>	0.250¢	effective January 1, 2003
<u>Renewables Charge per kWh</u>	0.050¢	effective January 1, 2003

#### Rates for Supplier Service

<u>Default Service Charge per kWh</u>	per Tariff for Default Service
---------------------------------------	--------------------------------

#### Interruptible Credit

IC-1	\$5.78
IC-2	\$7.88

#### Minimum Charge

The monthly Customer Charge.

Other Rate Clauses apply as usual.

(1) Includes Default Service Adjustment Factor of 0.003¢ per kWh, Residential Assistance Adjustment Factor of 0.014¢ per kWh, and Default Service Cost Reclassification Adjustment Factor of (0.127¢) per kWh.



### D.3 R-3 Residential Time-of-use

MASSACHUSETTS ELECTRIC COMPANY

Residential - Time-of-Use (Optional) R-4  
M.D.T.E. No. 1107

Effective  
March 1, 2007

Adjusted by:

Transition Cost Adjustment	March 1, 2007
Transmission Service Cost Adjustment	March 1, 2007
Default Service Adjustment	March 1, 2007
Residential Assistance Adjustment	March 1, 2007
Default Service Cost Reclassification Adjustment	November 1, 2007

Monthly Charge as Adjusted

Rates for Retail Delivery Service

<u>Customer Charge</u>	\$20.18	
<u>Metering Charge</u>	If applicable	
<u>Distribution Charge per kWh (1)</u>		
Peak Hours Use	6.312¢	
Off-Peak Hours Use	0.320¢	
<u>Transmission Charge per kWh</u>	1.033¢	
<u>Transition Charge per kWh</u>		
Peak Hours Use	1.244¢	
Off-Peak Hours Use	0.056¢	
<u>Demand Side Management Charge per kWh</u>	0.250¢	effective January 1, 2003
<u>Renewables Charge per kWh</u>	0.050¢	effective January 1, 2003

Rates for Supplier Service

<u>Default Service Charge per kWh</u>	per Tariff for Default Service
---------------------------------------	--------------------------------

Minimum Charge

The monthly Customer Charge plus the applicable Metering Charge, if any.

Other rate clauses apply as usual.

(1) Includes Default Service Adjustment Factor of 0.003¢ per kWh, Residential Assistance Adjustment Factor of 0.014¢ per kWh, and Default Service Cost Reclassification Adjustment Factor of (0.127¢) per kWh.

## D.4 G-1 General Service – Small Commercial and Industrial

### MASSACHUSETTS ELECTRIC COMPANY

General Service-Small Commercial & Industrial G-1  
M.D.T.E. No. 1108

Effective  
March 1, 2007

Adjusted By:

Transition Cost Adjustment	March 1, 2007
Transmission Service Cost Adjustment	March 1, 2007
Default Service Adjustment	March 1, 2007
Residential Assistance Adjustment	March 1, 2007
Default Service Cost Reclassification Adjustment	November 1, 2007

#### Monthly Charge as Adjusted

#### Rates for Retail Delivery Service

<u>Customer Charge</u>	\$8.74	
<u>Location Service Charge</u> - For allowed unmetered service	\$6.80	
<u>Distribution Charge per kWh (1)</u>	4.017¢	
<u>Transmission Charge per kWh</u>	1.149¢	
<u>Transition Charge per kWh</u>	0.373¢	
<u>Demand Side Management Charge per kWh</u>	0.250¢	effective January 1, 2003
<u>Renewables Charge per kWh</u>	0.050¢	effective January 1, 2003

#### Rates for Supplier Service

Default Service Charge per kWh Per Tariff for Default Service

#### Minimum Charge -

The applicable monthly Customer Charge or Location Service Charge, provided, however if the KVA transformer capacity needed to serve a customer exceeds 25 KVA, the minimum charge will be increased by \$1.83 for each KVA in excess of 25 KVA.

Other Rate Clauses apply as usual.

(1) Includes Default Service Adjustment Factor of 0.003¢ per kWh, Residential Assistance Adjustment Factor of 0.014¢ per kWh, and Default Service Cost Reclassification Adjustment Factor of (0.040¢) per kWh.

## D.5 G-2 General Service – Demand

### MASSACHUSETTS ELECTRIC COMPANY

General Service - Demand G-2  
M.D.T.E. No. 1109

Effective  
March 1, 2007

Adjusted by:

Transition Cost Adjustment	March 1, 2007
Transmission Service Cost Adjustment	March 1, 2007
Default Service Adjustment	March 1, 2007
Residential Assistance Adjustment	March 1, 2007
Default Service Cost Reclassification Adjustment	November 1, 2007

#### Monthly Charge as Adjusted

#### Rates for Retail Delivery Service

<u>Customer Charge</u>	\$16.01	
<u>Distribution Demand Charge per kW</u>	\$6.21	
<u>Distribution Energy Charge per kWh (1)</u>	0.147¢	
<u>Transition Demand Charge per kW (2)</u>	\$0.44	
<u>Transition Charge per kWh (3)</u>	0.262¢	
<u>Transmission Charge per kWh</u>	1.132¢	
<u>Demand Side Management Charge per kWh</u>	0.250¢	effective January 1, 2003
<u>Renewables Charge per kWh</u>	0.050¢	effective January 1, 2003

#### Rates for Supplier Service

<u>Default Service Charge per kWh</u>	per Tariff for Default Service
---------------------------------------	--------------------------------

#### Minimum Charge

The Customer Charge plus the Demand Charge.

Other Rate Clauses apply as usual.

- (1) Includes Default Service Adjustment Factor of 0.003¢ per kWh, Residential Assistance Adjustment Factor of 0.014¢ per kWh, and Default Service Cost Reclassification Adjustment Factor of (0.014¢) per kWh.
- (2) Includes Contract Termination Charge mitigation of (\$2.69) per kW.
- (3) Includes Contract Termination Charge mitigation of (1.550¢) per kWh and Transition Charge Adjustment Factor of (0.007¢) per kWh.

## D.6 G-3 Time-of-use

### MASSACHUSETTS ELECTRIC COMPANY

Time-of-Use - G-3  
M.D.T.E. No. 1110

Effective  
March 1, 2007

Adjusted By:

Transition Cost Adjustment	March 1, 2007
Transmission Service Cost Adjustment	March 1, 2007
Default Service Adjustment	March 1, 2007
Residential Assistance Adjustment	March 1, 2007
Default Service Cost Reclassification Adjustment	November 1, 2007

#### Monthly Charge as Adjusted

#### Rates for Retail Delivery Service

<u>Customer Charge</u>	\$70.72	
<u>Distribution Demand Charge per kW</u>	\$3.80	
<u>Distribution Energy Charge per kWh (1)</u>		
Peak Hours Use	1.249¢	
Off-Peak Hours Use	0.017¢	
<u>Transition Charge per kW (2)</u>	\$0.75	
<u>Transition Charge per kWh (3)</u>	0.140¢	
<u>Transmission Charge per kWh</u>	1.032¢	
<u>Demand Side Management Charge per kWh</u>	0.250¢	effective January 1, 2003
<u>Renewables Charge per kWh</u>	0.050¢	effective January 1, 2003

#### Rates for Supplier Service

<u>Default Service Charge per kWh</u>	per Tariff for Default Service
---------------------------------------	--------------------------------

#### Minimum Charge

The monthly Customer Charge plus the Demand Charge.

Other Rate Clauses apply as usual.

- (1) Includes Default Service Adjustment Factor of 0.003¢ per kWh, Residential Assistance Adjustment Factor of 0.014¢ per kWh, and Default Service Cost Reclassification Adjustment Factor of (0.011¢) per on-peak kWh.
- (2) Includes Contract Termination Charge mitigation of (\$4.51) per kW.
- (3) Includes Contract Termination Charge mitigation of (1.360¢) per kWh and Transition Charge Adjustment Factor of (0.036¢) per kWh.

## Appendix E. Additional Experiments

### E.1 Transformer life

Calculations show that the introduction of 150000 PHEV's in the state of Massachusetts would have almost no change on the life of the transformer. To compute these calculations two basic assumptions were made. The first was that all substations are connected together and that the load can be shared between all substations equally. Secondly, it was assumed that charging would only take place at night, when the load curve is in a trough period. The following calculations were made:

$$\text{Voltage required to charge a car} = 120V$$

$$\text{Current required to charge a car} = 13A$$

$$\text{Charging time} = 4\text{hrs}$$

$$\text{Power consumed by each car per hour} = (120 \times 13 \times 4)/4 = 1560 \text{ W} = 1.56 \text{ kW}$$

$$\text{Power consumed by 150,000 cars} = 1560 \times 150,000 = 234 \text{ MW}$$

$$\text{Power consumed by 150,000 cars in MVA} = 2.34\text{MW}/0.8 = 292.5 \text{ MVA}$$

$$\text{Number of transformers in Massachusetts} = 500$$

$$\text{Additional load per transformer} = 292.5 / 500 = 0.585 \text{ MVA}$$

This additional load is very small and is added during the trough period, which further subdues its effect on transformer life. The model reflected the mathematical derivations and showed no change in the life of the transformer, which stood at 170 years. When number of cars was doubled to 300000, the life of the transformer came down to 169 years, reinforcing the assumption that the number of cars has little effect on the life of the transformer.