Platinum Supply and the Growth of Fuel Cell Vehicles

Justin Boudreau, Eugene Choi, Ravindra Datta, Oljora Rezhdo, Khalid Saeed

Worcester Polytechnic Institute, 100 Institute Road, Worcester, MA 01609-2280, USA

Abstract

This report addresses problems associated with U.S. fuel cell vehicle production and a limited platinum supply. Polymer Electrolyte Membrane (PEM) fuel cells, which use a platinum catalyst, could place strain on the platinum market if fuel cell vehicles are widely produced. We developed a dynamic hypothesis, identified causal relationships, and created a system dynamics model in *iThink*. Based on this model, we found platinum prices would likely reach $50,000 per kilogram in 30 years and the cost of platinum for a fuel cell vehicle would be $2,500. At this price, the platinum barrier is surmountable if the cost of other FCV components is drastically reduced. If a world FCV market takes hold, it was concluded that only about 15% global market penetration is feasible.

1: Introduction and Background

1.1: Introduction

Oil plays a pivotal role in today's world, accounting for around 36% of worldwide energy use [1]. Unfortunately, many nations have already reached peak oil production and are now producing less and less oil per year. The United States is an excellent example; in 1970, the U.S. oil production peaked at just below ten million barrels per day [2]. Ever since, U.S. oil production has been decreasing; in 2007, oil production was just five million barrels per day. While the U.S. is still a significant oil producer, it is also the largest oil consuming nation on Earth. The United States consumed an astonishing 23.9% of the world's supplied oil in 2007; for comparison, China, the second most oil consuming nation, only had 9.3% [3]. While oil production and consumption is a worldwide issue, it is of particular importance to the United States. Consuming nearly a quarter of the world's oil and faced with depleting oil production, energy has become one of the most important problems facing the nation.

In addition to concerns over depleting oil production, there are environmental issues to consider. One of the largest concerns is the effect of greenhouse gasses on global warming. In the 2006 U.S. Climate Action Report, it was reported that U.S. CO_2 emissions for 2004 was 7,074.4 Tg (707 million metric tons). This was a 15.8% increase from 1990. The report attributed the rise in emissions to increases in electricity demand, expanding industrial production, and increased travel [4]. With more vehicles on the road emitting carbon dioxide, it is becoming more important to consider the environmental impacts of conventional internal combustion engines.

One plan to reduce oil dependency and carbon emissions is to replace internal combustion engine vehicles with fuel cell vehicles (FCVs). These vehicles are more efficient (30% wells-to-wheel efficiency compared to a 15% wells-to-wheel efficiency for internal combustion engine vehicles [5]). Polymer Exchange Membrane (PEM) fuel cells are currently regarded as one of the most viable types of fuel cells for automotive use due to their low operating temperature (only around 80°C [6]). The automotive industry has already begun producing FCVs on a small scale for testing purposes and to raise public awareness. Some manufacturers have gone further; in the summer of 2008, Honda began to lease a small number of FCVs to the public in California. In addition to automotive developments, the infrastructure necessary to support FCV fleets is being established in Norway with the HyNor project and in California with the California Hydrogen Highway Network (CaH_2Net).

While these projects have provided useful information on the small scale development of fuel cell vehicles, many concerns still exist, especially when considering large scale market penetration of FCVs.

Some of these concerns are currently being addressed; for example, the storage of hydrogen is improving with stronger tanks capable of storing hydrogen at 10,000 psi [6], the public is becoming increasingly aware of fuel cell technology and the benefits it offers, and infrastructure is being developed in selected areas. However, some concerns still need further investigation.

In particular, a limited platinum supply needs to be taken into account when considering the development of fuel cell vehicles. Currently, fuel cells have a platinum loading of about 0.5 to 0.6 mg/cm^2_{MEA} (on an experimental level, loadings have been as low as 0.25 $mg/\ cm^2_{MEA}$) and a power density around 0.9 W/cm^2_{MEA} [7]. This translates to 0.6 to 0.67 mg/W; from this result, a 100 kW FCV would require 60 to 67 grams of platinum. In November of 2008, the average price of platinum was $844.21 per troy ounce ($24.31 per gram) [8]. For a 100 kW vehicle, the cost of the platinum catalyst alone would be $1,600. Other components of the fuel cell, such as the Nafion membrane, will drive the cost even further. To put this in perspective, a complete internal combustion engine costs about $2,500 to $3,500 [9]. The cost of platinum alone is approximately half the cost of a fully functional internal combustion engine. While the costs for fuel cells may go down due to technological advances that result in a smaller platinum loading, the price of platinum may increase as FCVs are introduced. In addition to price, there are other concerns such as limited platinum reserves. Platinum, being one of the rarest metals on Earth, is difficult to mine. For every 7 to 12 tons of ore mined, only about one ounce of platinum is produced [10]. Due to its extreme rarity, there is the possibility that the amount of mineable platinum could dramatically decrease in the future.

1.2: Background

Past studies on the interrelation between the platinum and FCV market have been inconclusive. Some studies, such as those by *TIAX* LLC and R.J. Spiegel have concluded that it is feasible for an FCV market to develop. However, a study by Robert H. Borgwardt suggested that it platinum was a limitation on FCV market growth.

TIAX, a technology processing company, has done extensive research on the prediction of FCV growth with the U.S. Department of Energy. With scenarios based on different levels of FCV market penetration, *TIAX* concluded that when 50% of new vehicle sales are occupied by FCVs, the increase in FCV demand can be supported by the world platinum supply [11]. Industrial experts and the Department of Energy (DOE) suggest that the rate of increase in platinum demand on the order of 12Mg/year is feasible [11]. The increase in demand has been about 6Mg/year for past years since 1988 [12], and with the scenario of 50% market penetration by year of 2050, the sharpest increase will occur in 2030, lasting for about 15 years with a demand growth rate of 12Mg/year [11]. The model predicts that eventually the demand will remain at about 700Mg/year with no increase in the rate of demand growth.

However, supply isn't the only consideration; the change in the price of platinum due to increased demand needs to be considered. One study suggests that the highest increase in price for platinum will not exceed 12.5% [13]. The model assumes a 95% rate of recycling, a platinum loading of 20g per vehicle, and the eventual decrease in platinum demand with the advance of technology. While the experimental results corroborate very high recycling rate from used fuel cells [14], the assumption of a significant decrease in demand within two decades seems to be overly optimistic. It is known that there is currently no viable alternative to platinum as a catalyst for fuel cells in vehicles [15]. Palladium may be able to substitute some portion of platinum demand, but it offers little advantage in terms of cost and availability [15].

Other studies have noted the optimistic assumptions used in past models. In fact, most analysis based on information reflecting the current level of technology show that the supply may not be sufficient to meet worldwide platinum demand. The alternative assumptions include: [15]

- South African supply (80% of world platinum production) can only be increased by 4% per annum instead of 5%.
- Jewelry demand grows at more than 2% per annum – it is either assumed to remain constant or decrease as the platinum demand by FCV increases.
- Fuel cell stacks require more than 20g Pt/vehicle – this is less than half of the amount that is currently being used.
- The demand for cars grows by more than 55% per decade, instead of 45-50%.

The high sensitivity of the results from past models is due to the absence of feedback loops within the model. Without important feedbacks, the model can't respond to changes within the system, resulting in high sensitivity. With these models, results have largely been inconclusive, with large variations in results among different studies. It should be noted, however, that many models make conclusions based on relaxed constraints, despite the sensitivity of the model to those constraints. Also, most analysis does not reflect practical market penetration, as they do not include the response of FCV production to platinum prices. The uncertainties presented due to the relaxation of constraints suggest that the future research should focus on assessing costs associated with increasing platinum production and platinum market dynamics [16].

In a 2001 study from the US Environmental Protection Agency, authored by Robert H. Borgwardt [12], it was estimated that platinum could dramatically inhibit the production of fuel cell vehicles. The report also found that it would take an estimated 66 years and a total 10,800 tons of platinum to convert the entire US fleet to fuel cell powered vehicles. This conclusion was based on the assumption that US platinum consumption was at 48% of the worldwide supply. If US platinum consumption was at 16% (the percentage consumed in 2001) then it was concluded that it would take 146 years for complete conversion. In a 2004 study [17], also from the US Environmental Protection Agency, a different conclusion was reached. Under the authorship of R.J. Spiegel, the study found that only 4% of the world's platinum supply is needed to meet fuel cell vehicle demand until 2035.

While these studies are informative and supply valuable data and predictions, the large variation among studies prevents one from arriving at any solid conclusion about platinum supply and fuel cell vehicle production. In addition, previous models often did not consider the interactions among variables which give rise to important behavior. The system dynamics model used in this report takes these interrelations into account, providing a more detailed picture of the possible consequences of an FCV market.

2: Methodology and Analysis

Modeling complex problems, such as the issue of platinum limitations in an emerging FCV market, requires a model that considers feedback effects and how these effects reverberate through the model. System dynamics takes important feedback loops and interrelations into account, resulting in a more realistic model.

2.1: Establishing Reference Modes: The Computational Model

Before developing the system dynamics, a computational model was developed as a reference mode. The purpose of the computational model is to obtain a qualitative understanding of how the platinum market will behave under the strain of FCV production.

Establishing possible scenarios concerning platinum supply limitations involves developing numerous assumptions. These assumptions must take many factors into account, such as the predicted number of FCVs to be produced within the next few decades, the platinum loading per vehicle, and efficiency of platinum recycling programs. The first assumption concerns the annual growth rate of the U.S. vehicle fleet. As of 2006, there were approximately 250 million vehicles on the road [18]. Data of US vehicle sales were available from 1990 to 2007 by the U.S. Bureau of Transportation Statistics. For 2007, approximately 8 million passenger vehicles were sold in the United States [19]. This value will provide the market saturation point for FCVs.

The second assumption concerns the annual growth rate of platinum production. From 1985 to 2003, the supply of platinum has increased by an average of 6,150 kg per year [20]. The USGS estimated that the platinum supply could increase anywhere between five and fifteen thousand kilograms per year. For the computational model, it was assumed that the platinum supply will increase by ten thousand kilograms per year.

The third assumption is an estimate of the future market penetration of fuel cell vehicles. The estimates that will be used for our modeling purposes will be the HyTrans model, developed by the U.S. Department of Energy in 2005. Unlike many previous models, the HyTrans model incorporates significant hindrances to the development of hydrogen fuel cell technology. The model takes into account factors such as the lack of a strong market for hydrogen fuel technology, the expensive price of fuel cells, and the need for development of economies of scale in vehicle production. The model itself is based on a collection of more specific models. These models include the DOE H2A Model for hydrogen production and delivery, PSAT & ASCM Vehicle Performance and Cost Estimates model, ORNL Vehicle Choice model, ORNL Advanced Vehicle Manufacturing Cost model, GREET GHG Emissions model, and the NEMS AEO 2006 model [21]. The HyTrans model estimated FCV market penetration until 2025 under three different scenarios. The results from the HyTrans model were qualitatively extended until market saturation was achieved.

The final assumptions concern platinum loading for fuel cell vehicles, the efficiency of platinum recovery programs, and the average life of a fuel cell vehicle. In an article by Mark F. Mathias et al [7] , it was reported that platinum loadings of 0.25 mg/cm^2 were achieved on an experimental level. In addition to breakthroughs in platinum loadings, power density has increased. The article cites power densities of about 0.9 W/cm^2. Using this information, it was determined that the average amount of platinum per automobile would be about 22 g (for an 80 kW vehicle). In a report by Stephen Grot and Walther Grot of Ion Power Inc. in conjunction with the US Department of Energy [22], a method of platinum recycling was found to recover about 95% of platinum from a fuel cell. Articles published by Robert H. Borgwardt [12] and R.J. Spiegel [17] use an average FCV lifespan of 15 years. This value far exceeds the current lifespan of about 5 years [23] but is used in the ideal case where FCV life expectancy is increased through technological breakthroughs. The average lifespan of a fuel cell vehicle is taken to be 15 years for the computational model.

Using these assumptions, a rudimentary model was developed to give a better estimate of platinum demand for FCVs in the future. The computational model suggests that platinum demand will increase dramatically at the beginning. However, as recycling of platinum from old FCVs begins to take hold, the demand for platinum would quickly decrease. Depending on the annual growth of the global platinum supply, US FCV platinum demand could peak at 17 to 33% of world-wide platinum demand (see Figure 1).

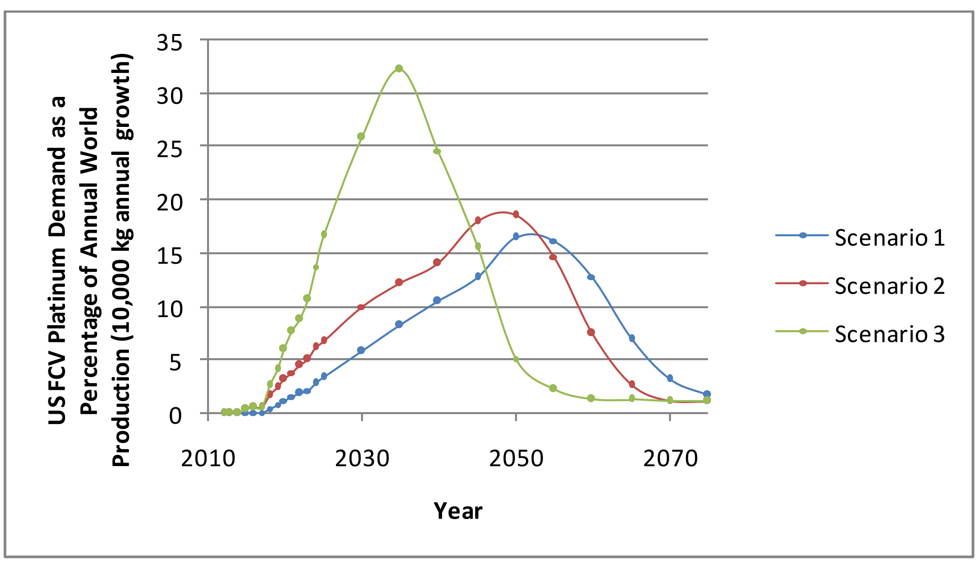

Figure 1: US FCV Platinum Demand as a Percentage of Annual World Production (10,000 kg annual growth)

While the computational model does offer some insight on the problem at hand, there are limitations to what can be extracted from the results. Firstly, many of the assumptions are based on ideal conditions. For example, the FCV life that was used for the computational model (15 years) greatly exceeds the current life expectancy of 5 years, but it was used under the assumption that the lifespan of FCVs would increase over time. Another weakness of the computational model is that it does not take into account feedback structures that could dramatically affect the outcome of the model. In this model, annual world production is assumed to increase at a constant rate. In reality, world production is strongly dependent on platinum demand. If there's a large demand for platinum, world production could decrease dramatically. If demand suddenly falls, so could world production. These causal links, which have been neglected for the purpose of the computational model, are an integral part of the system dynamics model.

2.2: Formulation of Dynamic Hypothesis

Using the reference mode and research that has already been done, it is possible to establish a dynamic hypothesis. From the reference mode, it appeared that recycling will play an important role in the model. If recycling is prominent enough, it could cause a "boom and bust" scenario for platinum mines. There's the initial mining boom due to increased consumption, but as old FCVs are recycled, secondary platinum is introduced into the market causing a bust for the platinum mining industry. These two competing forces form two of the model's most important feedback loops, seen in Figure 2.

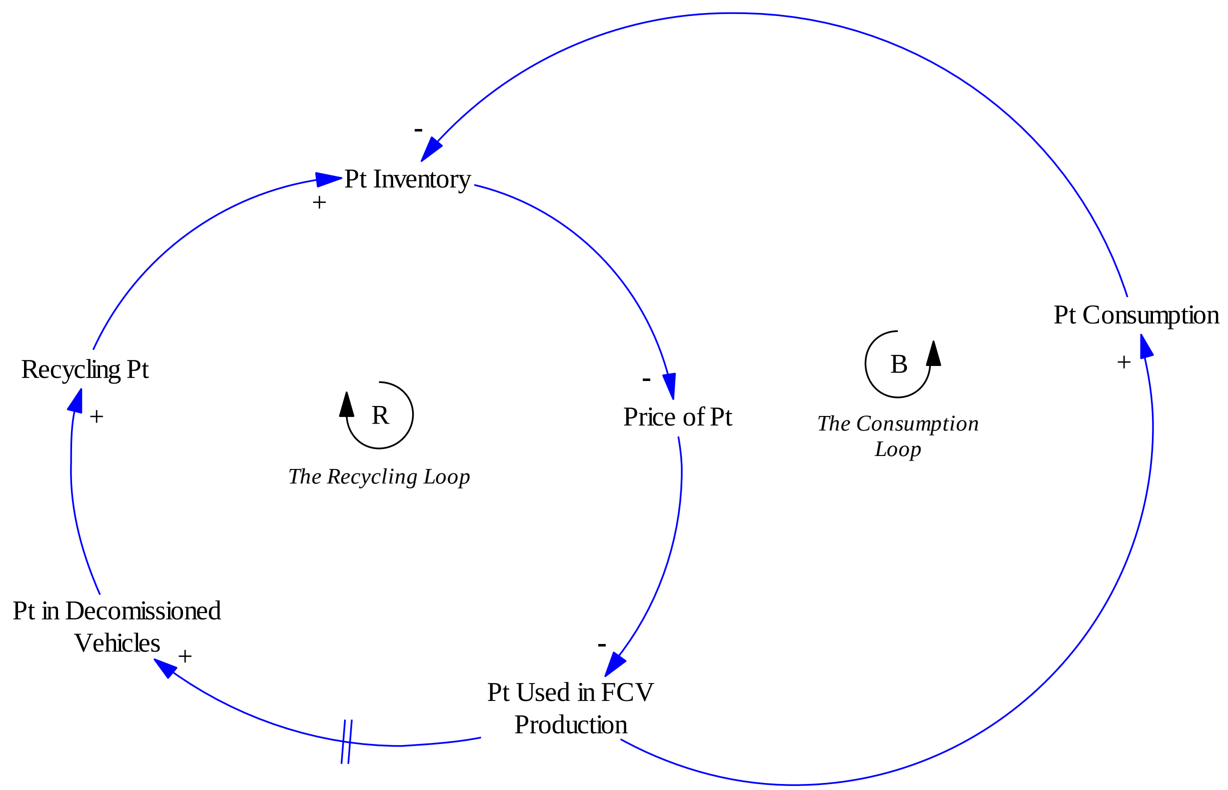

Figure 2: The Recycling and Consumption Feedback Loops

As FCV production increases, platinum consumption will increase. The increase in consumption will reduce the amount of platinum available on the market. The price of platinum will increase due to limited supply. The rise in platinum prices will then cause a decrease in FCV production. This logic comprises a balancing feedback loop (the Consumption Loop).

The Recycling Loop is a reinforcing feedback. As FCV production increases, the platinum in decommissioned vehicles increases. However, there is a delay from newly produced FCVs to decommissioned vehicles due to the lifespan of the FCV. The increase in platinum from decommissioned vehicles results in an increase in platinum recycling. With more recycling, the platinum available on the market increases. Since there is an increase in platinum supply, the price of platinum falls. The reduction in platinum prices encourages more FCVs to be produced.

2.3: Creating the Simulation Model

The next step in developing this model is to translate the qualitative representation of the problem seen in the Causal Loop Diagram to a quantitative representation that uses mathematical equations to represent causal links and the transportation of ideas and materials through the system. The simulation model structure can be seen in Figure 3.

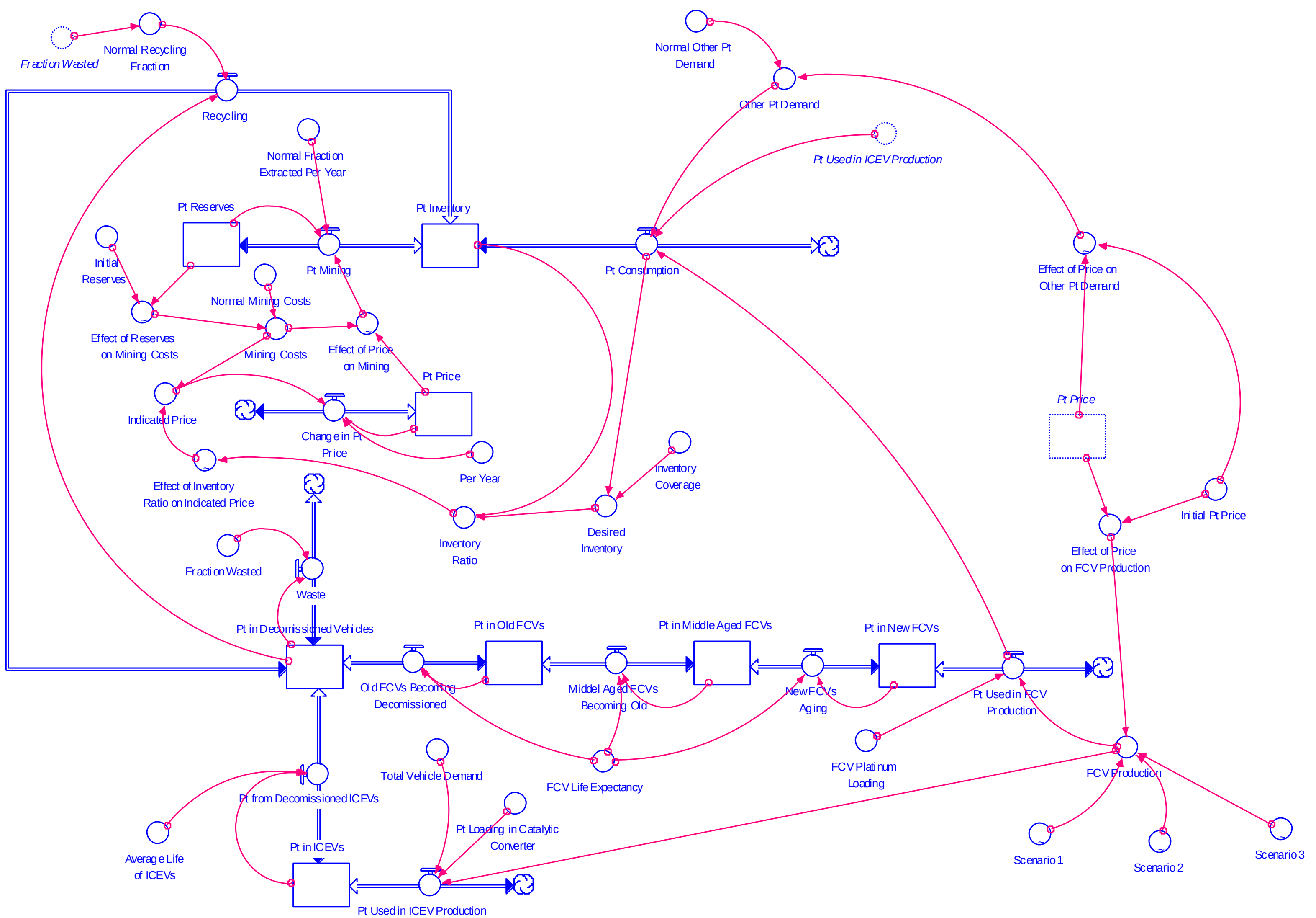

Figure 3: The iThink Model

The first flow, “Pt Used FCV Production” is defined by FCV Production and platinum loading. FCV Production is defined by three different scenarios which are in the form of graphical functions and it is affected by price through a graphical function; this function is a representation of elasticity of demand for FCVs. These three scenarios are based off past research; in particular the results from the HyTrans model (see Table 3) are fit to a Gompertz function. These three scenarios capture different levels of FCV market penetration (half a million, one million, and 2.5 million per year by 2025 for each scenario respectively). FCV platinum loading is multiplied by FCV Production to give the amount of platinum used in FCVs per year. The next three stocks and their respective flows represent the lifecycle of an FCV. It is expanded as a third-order material delay in order to achieve a more discrete delay.

After the lifecycle of the FCV is completed, the FCV is recycled for valuable material. However, not all the platinum can be recycled. Some of it is lost due to inefficiencies during the recycling process. This is represented by “Fraction Wasted”. In addition to FCVs, there are also internal combustion engine vehicles (ICEVs) to consider. ICEV production is modeled as a function of Total Vehicle Demand and FCV Production. As established in the computational model, Total Vehicle Demand is assumed to remain at about 8 million vehicles per year. ICEV production is this value minus the FCV production (for each FCV produced, there is one less ICEV that would have been produced). The FCV and ICEV platinum loadings are used to convert the number of ICEVs to an equivalent value in kilograms of platinum. Due to the small amount of platinum in catalytic converters, the delay due to lifespan is just represented as a first-order delay. For this model, the average lifespan for ICEVs was assumed to be 12 years [24].

Recycle is determined simply by subtracting the Fraction Wasted from 1. In addition to the recycle entering the inventory, there is the platinum from mining and the initial value for the platinum inventory. For 2007, approximately 200,000 kg of platinum was mined [25]; this value was used for the initial platinum inventory. Platinum mining is a function of the reserves and price. Price effects mining through a graphical function and models the elasticity of supply. The auxiliary "Normal Fraction Extracted per Year" is the fraction extracted relative to the reserves. The initial value for the reserves is based on a report in the South African Journal of Science by R.G. Cawthorn that estimates 48,000,000 kg of platinum exists worldwide [26]. Using the initial values for the platinum inventory and reserves, the normal fraction extracted per year was determined to be 0.00417. In addition to the effects of price, mining is defined as the reserves multiplied by the normal fraction. Since the reserves have no inflow (limited by what's in the Earth), the depleting reserves reduce the amount mined as time goes by.

Platinum is added to the inventory through recycling and mining and it is removed through consumption. Platinum consumption is defined as the summation of platinum for FCV production, for ICEV production, and for all other sources. It is important to note that FCV and ICEV production is for the U.S. only while other platinum demand is global (including ICEV production other than the U.S.). Other platinum demand is defined by a normal demand and an elasticity of demand represented by a graphical function. The normal demand is assumed to be 190,000 kg per year. This is slightly less than the 200,000 kg produced because U.S. ICEV platinum demand is considered separately. The platinum for ICEV production is not influenced by price directly since catalytic converters have a small platinum loading when compared to fuel cells.

One of the most vital components of the model is price. The initial value of price is set to $35,000 per kg, based on a 5-year historical price [27]. It's worth noting that mining costs are also initially set at $35,000 in order to start in equilibrium. The actual mining costs are very close to this value, around $33,000 for the Anglo Platinum mining company based in South Africa [28]. Price is influenced by indicated price, which is simply the mining cost multiplied by a graphical function of inventory ratio. The inventory ratio is the inventory divided by the desired inventory. The desired inventory is defined as platinum consumption multiplied by inventory coverage. The inventory ratio acts as a goal-seeking mechanism; if the desired inventory is greater than the actual inventory, prices will increase until the actual inventory is the same as the desired inventory. If the desired inventory is less than the actual inventory, prices will decrease until to the goal (actual equals desired) is reached. However, the inventory does not directly influence price. The ratio influences the indicated price through a graphical function. The indicated price minus the actual price will be the change in price. By having platinum consumption and the platinum inventory influence price through this mechanism, oscillations in price will be smoothed out, making the results clearer to see.

Chapter 3: Results and Discussion

3.1: Model Limitations

One of the most important simplifying assumptions of this model is that the platinum market operates under pure competition. The inventory mechanism that is used in the model is effective at emulating supply and demand behavior but it does have limitations. The mechanism establishes goal-seeking behavior that results in equilibrium when platinum price equals cost (where the cost includes a normal profit). Under these conditions, an economic profit is never sustained. In other words, the mechanism replicates a purely competitive market. Unfortunately, the platinum market is not likely to be purely competitive. Only a few mining companies operating in South Africa are responsible for the majority of the world's platinum production. With so few companies having such a large market share, it is likely that a cartel could develop. Instead of a purely competitive market, the market is most likely to be dominated by an oligopoly of platinum mining firms. Increasing platinum demand due to FCVs may result in these companies participating in price fixing schemes to increase profits. This is one of the larger weaknesses of the model and could be improved upon in future work.

3.2: Scenario Analysis

Three scenarios were established for this model; these scenarios were designed to cover a wide range of assumptions. The values for all three scenarios are summarized in Table 1.

Table 1: Scenario Analysis

	Worst Case	Middle Ground	Best Case
Normal Change in FCV Population	Scenario 3 (rapid growth)	Scenario 2 (steady growth)	Scenario 1 (slow growth)
FCV Platinum Loading	0.100 kg	0.050 kg	0.020 kg
FCV Life Expectancy	12 years	8 years	5 years
Fraction Wasted	0.15	0.10	0.05

It is worth noting that the "best" and "worst" case scenarios are defined as the best and worst case scenarios for platinum prices. For example, the "best" case has an average FCV lifespan of only 5 years. Looking at the bigger picture, such a short lifespan is detrimental to the development of FCVs. However, in terms of platinum price, a short lifespan means a shorter delay in platinum recycling; this reduces the price of platinum. While the best and worst case scenarios are not very realistic, they provide a lower and upper bound on platinum price.

The results from the simulations show quite a large difference between the worst and best case scenarios (see Figure 4). Under the worst case scenario, prices skyrocket to $78,724 per kg in the first 30 years. Afterwards, recycling begins and the price falls. Prices start to increase again as reserves diminish and it becomes more difficult to mine. The best case scenario has very little impact on the price. Instead of jumping to nearly $79,000, the price gradually rises to $41,967 in the first 30 years. Then the price rises even more gradually, starting to approach the "No FCV Production" line. The middle ground scenario has a noticeable increase in price by the year 30. At this point, the price is $50,146. For comparison purposes, the "No FCV" case has a platinum price of $39,433 per kilogram at year 30.

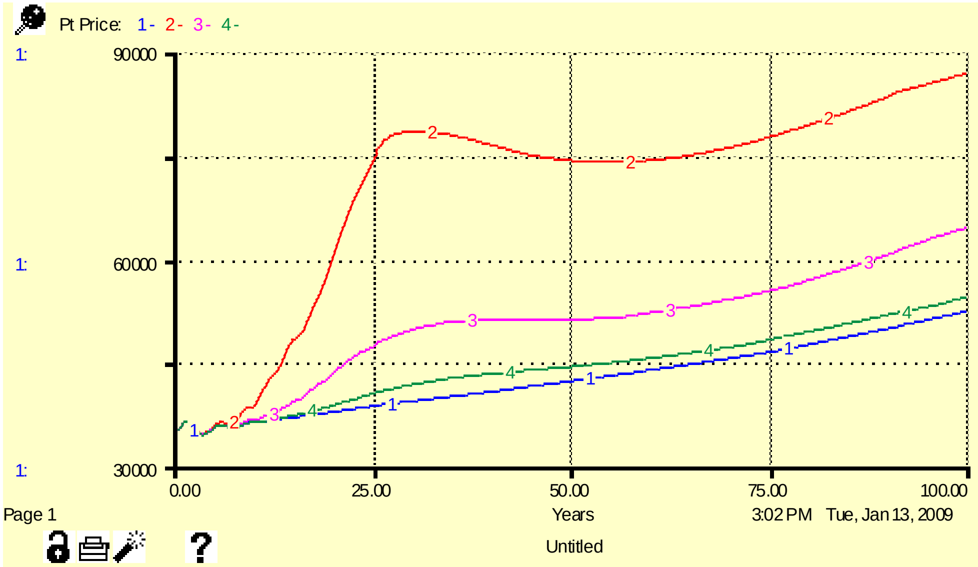

Figure 4: Platinum Price at Best through Worst Cases

Legend: Line 1: No FCV Production Line 2: Worst Case Line 3: Middle Ground Line 4: Best Case

3.3: Other Scenarios

Four other scenarios were tested using this model. The scenarios are as follows: improvements in platinum loading as price rises, the discovery of new mineable platinum reserves, a limitation on platinum mining, and a worldwide FCV population.

3.3.1: Improvements in Platinum Loading

This scenario operates under the assumption that as prices increase, there is more incentive to develop technologies that can reduce the amount of platinum needed per vehicle. In other words, as the price of platinum increases, the amount of platinum needed per vehicle decreases. This will decrease the demand of platinum and decrease the price of platinum, forming a balancing loop. The scenario parameters are seen in Table 2.

Table 2: Improvements in Platinum Loading

Variable	Value
Normal Change in FCV Population	Scenario 2
FCV Platinum Loading	Initially set at 50 grams (0.05 kg)
FCV Life Expectancy	8 years
Fraction Wasted	0.10

The results of the simulation can be seen in Figure 5. Price has little effect on the platinum loading during this period. However, as platinum prices continue to rise due to platinum reserves' depletion, the loading should become much smaller as new technologies are developed.

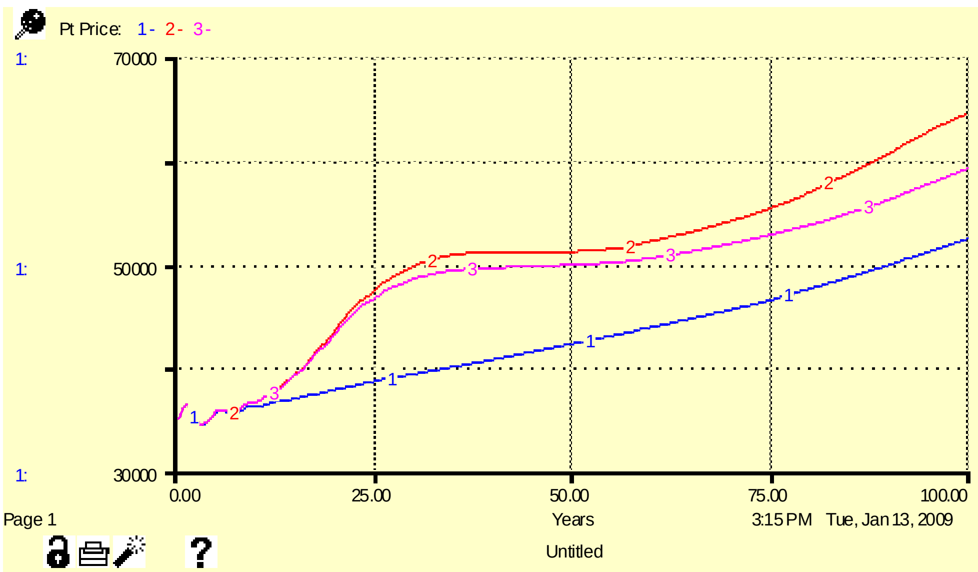

Figure 5: Platinum Price when Pt Loading Decreases with Price

Legend: Line 1: No FCV Production Line 2: Constant FCV Loading (0.05 kg Pt)
Line 3: Price/Loading Relation (0.05 kg initial loading)

3.3.2: The Discovery of New Platinum Reserves

In this scenario, new platinum reserves are discovered. The parameters for this scenario are the same as the previous scenario except that FCV platinum loading remains constant at 50 grams. It is assumed that 50,000 kg of platinum will be discovered per year. As can be seen from the results of Figure 6, when new Pt discoveries are made, the price increases less dramatically.

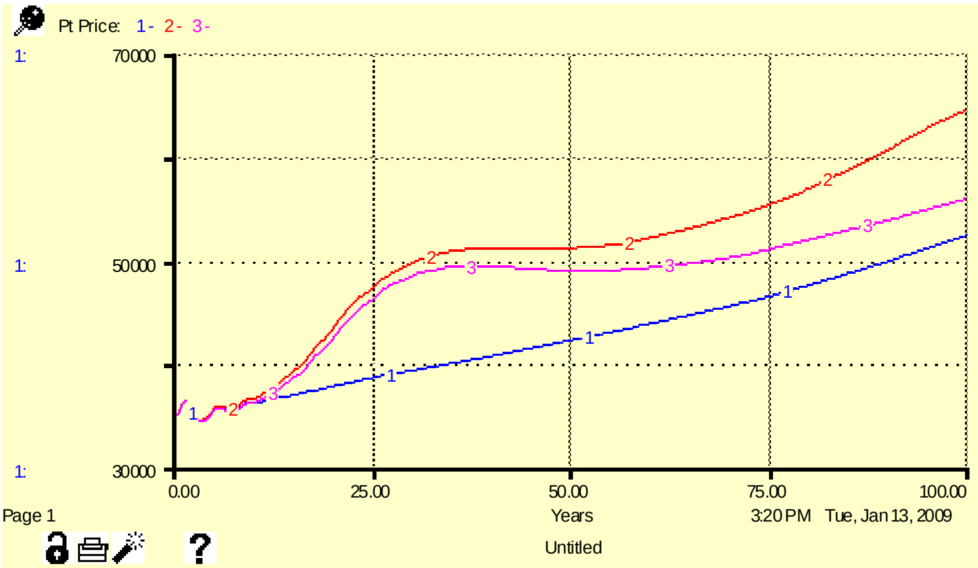

Figure 6: Effect of New Constant Yearly Reserve Discoveries on Pt Price

Legend: Line 1: No FCV Production Line 2: No Reserve Discovery
Line 3: Reserve Discovery

3.3.3: Limitations on Platinum Mining

In January of 2008, a major power crisis hit South Africa. South Africa's state-owned power supply company could not meet the electricity demand of the nation. As a result, many platinum mines were operating significantly below operating capacity or even not producing for extended periods of time. The result was a skyrocketing platinum price (see Figure 7).

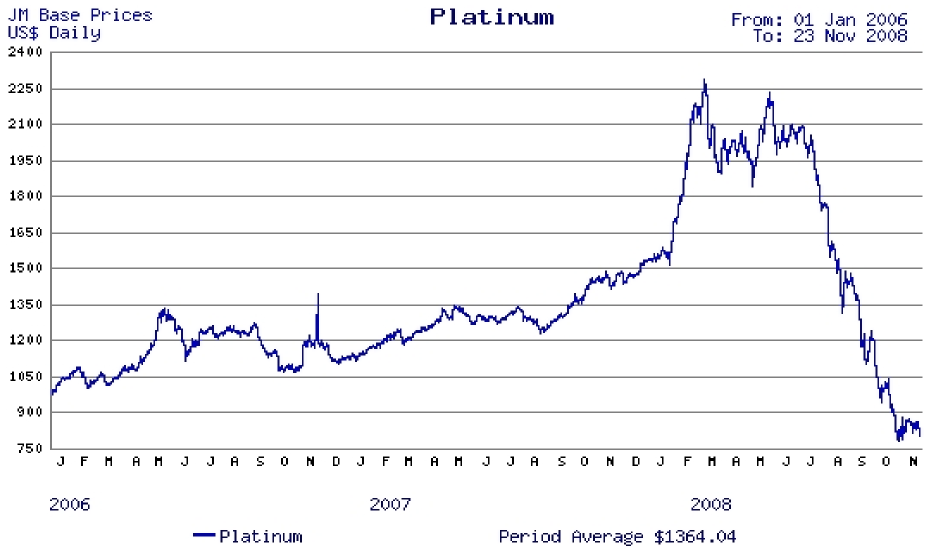

Figure 7: Platinum Price since 2006 [27]

Since then, prices have leveled off and then dramatically declined. However, what would happen if there was another power crisis (or any crisis that produced similar results)? What would happen if this crisis were to occur during peak FCV production? This is the focus of the next simulation.

In order to simulate a drastic drop in production and then a drastic increase in production once the crisis is resolved, two step functions were used in an auxiliary (called "Capacity Utilization"). The auxiliary is seen in equation 1.

$$Capacity\ Utilization = 1 - [STEP(0.5{,}10) - STEP(0.5{,}12)] \qquad (1)$$

The auxiliary was then multiplied by the Pt Mining stream. This results in a sudden decrease to half the normal capacity utilization for two years. At the end of the two years, capacity utilization jumps back to normal.

The results of the model show similar results to real life. When production was drastically reduced in January of 2008, prices soon shot up. A few months later, in July, the price began to fall as platinum mines began to utilize more of their capacity. The resulting flux of platinum on the market reduced prices. The model shows a similar spike in prices. After this initial jump, the price oscillates until it eventually follows the case where there was no crisis. In the long run, such an event would not have a significant impact on price, however, in the short run, there are dramatic price fluctuations. The results from the model can be seen in Figure 8.

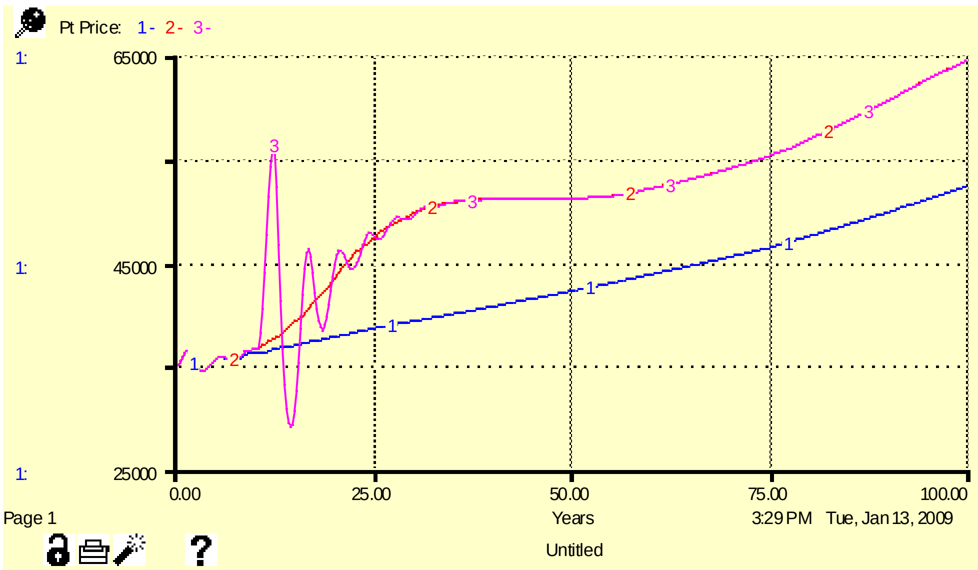

Figure 8: Pt Price as a Consequence of a Platinum Crisis

Legend: Line 1: No FCV Production Line 2: No Limits on Production
Line 3: Two Year Crisis Resulting in Half the Normal Production

3.3.4: Worldwide FCV Population

The previous scenarios operated under the assumption that only the United States would adopt Fuel Cell technology, which based on population constitutes only 4.6% of the entire world population. In reality, it is likely that other nations will use fuel cell technology. To consider worldwide demand of FCVs, slight alterations to the model were made. The total vehicle demand was changed from 8 million vehicles per year to 53 million vehicles per year [29].

With the model adjusted for a worldwide scenario, five different runs were considered. It was noticed that the platinum price would increase dramatically the first 25 years and then it would level off as soon as the recycling feedback begins to gain strength. These results are shown in Figure 9.

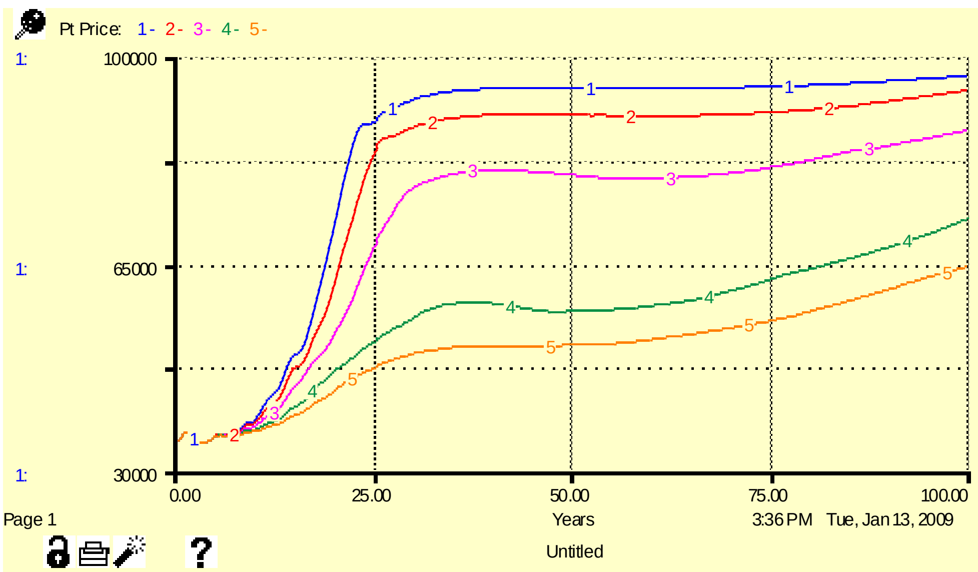

Figure 9: Pt Price based on different percentages of worldwide technology adoption

Legend:

Line 1. 100% worldwide adoption.
Line 2. 75% worldwide adoption.
Line 3. 50% worldwide adoption.
Line 4. 25% worldwide adoption.
Line 5. 15% worldwide adoption.

Chapter 4: Conclusions and Recommendations

Six different scenarios were tested using the model. These scenarios varied from generic “best” and “worst” case scenarios to specific circumstances and events that may have an effect on platinum and FCV market. It is important to note that the worst and best case scenarios do not reflect realistic outcomes; instead, they determine the maximum and minimum price range that can be expected. Depending on the conditions, it may or may not be feasible to develop fuel cell vehicles in the United States.

4.1: Worst Case

In the worst case scenario, there is a large platinum loading (100 grams) and an inefficient recycling process (85% efficient). In addition, the lifespan of FCVs is assumed to be just as long as ICEVs (12 years). This creates a longer delay before recycling begins to flood the platinum market. As a result, prices stay higher for a longer period of time. Finally, it is assumed that the growth of the FCV market is quite rapid. Under these extreme conditions, the price of platinum rises quite dramatically to nearly $79,000 per kg by the year 30 (2038). The price then falls due to recycling. However, by 2060, prices begin to rise again due to a shrinking reserve. Platinum reserves decrease from 48 million kg to around 17.2 million kg over the course of 100 years. In addition, the price of platinum reached $85,000 per kg by the year 100.

By 2038 (30 years), with the price of $78,724 per kg of platinum and a loading of 100 grams, the cost of platinum for a fuel cell vehicle would be $7,872. This is around three times the cost of a complete internal combustion engine. The costs due to platinum alone would inhibit the development of fuel cell vehicles. The decrease in reserves is also concerning. Within 100 years, the platinum reserves would be depleted by 64% from 2008. However, most of the depletion would be caused by other sources of demand since FCV recycling would largely be self-sustaining. The worst case scenario is infeasible; the cost of platinum is too high and there is a large decrease in platinum reserves.

4.2: Middle Ground

In the middle ground scenario, there is a platinum loading of 50 grams per vehicle, a more realistic lifespan of 8 years, a 90% efficient recycling process, and steady market growth. Compared to the worst case scenario, the price of platinum is only about $50,146 by 2038 instead of $78,724. At this price and at a loading of 50 grams per car, the cost of platinum per vehicle would be $2,507. This cost is comparable to a complete internal combustion engine. While it is still expensive, it is much more feasible than the worst case scenario. If the other components of the fuel cell, particularly the Nafion membrane, decrease in price due to increased production efficiency, then it could be possible to overcome the platinum price barrier. The reserves also depleted less quickly than the worst case scenario. Instead of decreasing to 17.2 million kg, the reserves decreased to 24 million kg. However, in 100 years, the price of platinum is quite high, near $65,000 per kg. By then, however, new technology could dramatically change the nature of FCVs or there could be a completely different alternative to FCVs. Overall, the middle ground scenario is feasible only if the other components of an FCV have dramatic reductions in price.

4.3: Best Case

For the best case scenario, the platinum loading is only 20 grams per vehicle, recycling is efficient at 95%, the lifespan of FCVs is short, resulting in a smaller delay before recycling takes effect, and FCVs are slowly introduced to the market. With these parameters, the price of platinum only reaches about $42,000 by 2038. Using the 20 gram loading, the cost of platinum per FCV is only $840. While still a significant component of the cost, it probably won't inhibit the development of FCVs, especially when considering likely price reductions in Nafion. The platinum reserves decreases to 28 million kg within 100 years; this difference is not as significant as the difference between the worst case and middle ground, but it is still worth mentioning. In 100 years, the price of platinum would be about $54,500. At a 20 gram loading, the price per vehicle is still reasonable at $1090. The best case scenario is feasible at these conditions.

4.4: Other Scenarios

In addition to the best through worst case scenarios, a few other scenarios were investigated. These scenarios include improvements in platinum loading with price, the discovery of new platinum reserves, and a supply crisis where platinum mines only produce half normal output due to a disaster.

Improvements in platinum loading with price are based on the notion that the higher the price of platinum, the more incentive there is to develop technology that reduces the platinum required. This scenario is largely dependent on defining factors such as the elasticity of technological breakthroughs and imposing technological limits: after a certain point, it becomes impossible to make improvements due to physical constraints. For this model, a graphical function was defined so that when the price of platinum is twice its initial cost, the platinum loading will be reduced by almost half. The effect of this scenario is noticeable but not very dramatic.

The discovery of new platinum reserves has a large impact on the model. In particular, the discovery of new reserves would significantly reduce the depletion of the reserves. Assuming a constant discovery of 50,000 kg per year, the reserves would only be reduced to 28.6 million kilograms after 100 years. This is comparable to the "best case" scenario, where the reserves were depleted to 28 million. The platinum price by 2038 would be $49,000 which is a little less than the middle ground scenario. A steady discovery of new reserves would result in a more sustainable scenario.

The third scenario is the platinum crisis; a situation where platinum mining is reduced due to a natural or man-made disaster. In an event similar to the power crisis in South Africa, the price of platinum would experience dramatic fluctuations in price over the course of the crisis and even a few years beyond the crisis. However, in the long-run, prices returned to the control case where there was no disaster. Therefore, such a crisis would probably have little effect on FCV market, especially in the long run.

The fourth scenario, worldwide production was used to see how the market would respond to global FCV adoption. With 100% global adoption, the price of platinum reached $93,500 per kilogram within 30 years. It wasn't until a market penetration of 15% was modeled that the scenario started to look feasible. At 15%, this price reached $50,000 within 30 years, proving much more feasible, but still a significant challenge.

4.5: Recommendations

After developing the system dynamics model and establishing several scenarios, it is clear that the development of fuel cell vehicles in the United States is largely dependent on factors such as platinum loading, FCV life expectancy, recycling efficiency, and how rapid FCVs are introduced to the market. Under the worst conditions, the development of the FCV market seems infeasible as the price of platinum per FCV is more than twice that of a conventional internal combustion engine. However, the FCV market isn't heavily limited by platinum in the middle ground scenario. It is still expensive, but it could be overcome by declining prices for other fuel cell components such as Nafion.

The middle ground scenario provides a basis for establishing goals with regard to fuel cell technology. If platinum loadings are 50 grams or lower, the average life is around 8 years, recycling efficiency is able to achieve 90% or better, and FCVs are not rapidly introduced into the market, then the platinum barrier can be surmounted as long as the price of other FCV components is reduced.

Worldwide production of FCVs is possible, but only on a small scale. FCV market penetration can only reach about 15% of global vehicle production before the price of platinum severely hinders production.

Appendix

Establishing FCV Production

Current sources regarding FCV Production are limited in their predictions. The research that currently has been done usually only considers FCV production in the next 20-30 years. Unfortunately, this time frame is not large enough to reach market saturation. As a result, current estimates had to be extrapolated to saturation. Future FCV market penetration was estimated by fitting a Gompertz function to available estimates from the HyTrans model (see Table 3). The Gompertz function is defined in equation 2.

$$y(t) = ae^{-be^{-ct}} \qquad (2)$$

The function behaves in a similar manner to that of a logistic function.

Table 3: HyTrans Model Predictions

Scenario 1	Scenario 2	Scenario 3
500,000 FCVs/year by 2025	1,000,000 FCVs/year by 2025	2,500,000 FCVs/year by 2025

Using this data, a Gompertz function was used to fit the points for each scenario. The resulting equations can be seen in equations 3 through 5 (also see Figure 10).

$$Scenario\ 1: y(t) = 8{,}000{,}000\ e^{-e^{-0.087t+2.5}} \qquad (3)$$

$$Scenario\ 2: y(t) = 8{,}000{,}000\ e^{-e^{-0.105t+2.5}} \qquad (4)$$

$$Scenario\ 3: y(t) = 8{,}000{,}000\ e^{-e^{-0.140t+2.5}} \qquad (5)$$

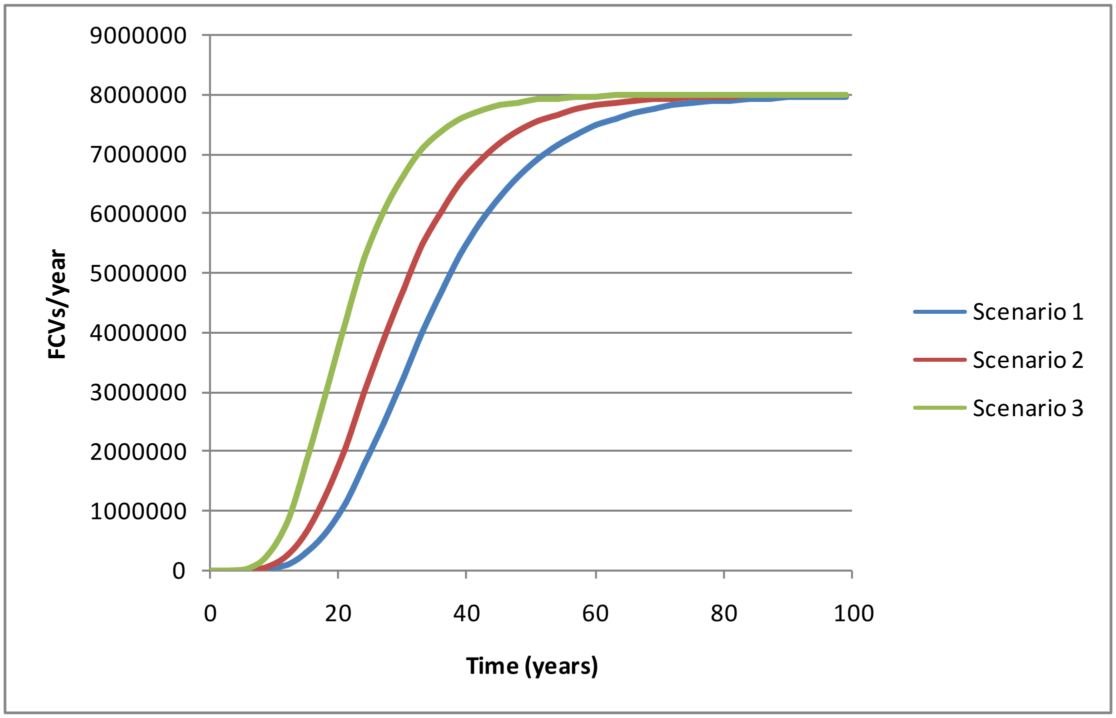

Figure 10: Predicted Annual FCV Growth Based on the HyTrans Model Fit to the Gompertz Function

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