THE STORAGE OF RENEWABLE ENERGY:
A COMPARATIVE EXAMINATION OF DEEP-CYCLE BATTERIES
AND HYDROGEN FUEL CELL SYSTEMS

Alex Waegel

A Thesis Submitted to the Faculty of the University of Delaware in Partial Fulfillment of
the Requirements for the Degree of Master of Arts in Urban Affairs and Public Policy

Spring 2010

Copyright 2010 Alex Waegel
All Rights Reserved
THE STORAGE OF RENEWABLE ENERGY:
A COMPARATIVE EXAMINATION OF DEEP-CYCLE BATTERIES
AND HYDROGEN FUEL CELL SYSTEMS

by

Alex Waegel

Approved__________________________________________________
John Byrne, Ph.D.
Professor in charge of thesis on behalf of the advisory committee

Approved__________________________________________________
Maria Aristigueta, D.P.A.
Director of the School of Urban Affairs and Public Policy

Approved__________________________________________________
Suzanne Austin, Ph.D.
Interim Dean of the College of Education and Public Policy

Approved__________________________________________________
Debra Hess Norris, M.S.
Vice Provost for Graduate and Professional Education
# TABLE OF CONTENTS

Table of Contents ................................................................................................................. i
List of Figures ....................................................................................................................... iii
List of Tables ......................................................................................................................... iv
Abstract .................................................................................................................................... v
1 Introduction ........................................................................................................................... 1
2 The Energy Problem ............................................................................................................ 5
3 The Development of Decentralized Power Production ......................................................... 19
   3.1 Past to Present ................................................................................................................. 20
       3.1.1 Rural Beginnings ................................................................................................. 20
       3.1.2 Energy Crisis ....................................................................................................... 20
       3.1.3 PURPA ................................................................................................................... 21
       3.1.4 Crash in the 1980s ............................................................................................... 23
   3.2 The Current Applications of Decentralized Power ......................................................... 24
       3.2.1 Rural Electrical Servicing .................................................................................... 24
       3.2.2 Green Energy Production ................................................................................... 25
       3.2.3 Net Metering, Load Shaping, and Peak Shaving .................................................... 26
       3.2.4 Summary of Current Decentralized Power Uses .................................................... 27
   3.3 The Current Limitations of Decentralized Generation ................................................. 28
       3.3.1 Higher Costs of Production .................................................................................. 29
       3.3.2 Intermittency ........................................................................................................ 32
       3.3.3 Other Limitations .................................................................................................. 35
4 History and Design of Electrochemical Batteries ............................................................... 39
5 History and Design of Hydrogen and Fuel Cells .................................................................. 47
   5.1 Decarbonization ............................................................................................................ 47
   5.2 How Fuel Cells Work ...................................................................................................... 50
   5.3 Sources of Hydrogen ..................................................................................................... 52
   5.4 Hydrogen Storage Techniques ...................................................................................... 57
   5.5 Fuel Cell Types .............................................................................................................. 60
   5.6 The Hydrogen Picture .................................................................................................... 61
6 The Future of Energy ........................................................................................................ 63

7 Efficiency and Loss ........................................................................................................ 71
  7.1 Deep-Cycle Battery Efficiency .............................................................................. 76
  7.2 Hydrogen and Fuel Cell Efficiency ....................................................................... 79
  7.3 Comparing Efficiencies ......................................................................................... 84
  7.4 Efficiency Conclusions ......................................................................................... 87

8 Technological Issues for Energy Storage ...................................................................... 89
  8.1 Energy Density ....................................................................................................... 91
  8.2 Comparative Technical Advantages ..................................................................... 100
  8.3 Technological Conclusions .................................................................................. 103

9 Economics and Expense ............................................................................................... 105
  9.1 The Expense of Transition .................................................................................. 106
  9.2 The Current System ............................................................................................. 107
  9.3 Expense ................................................................................................................ 108
  9.4 Scenarios ............................................................................................................... 113
  9.5 A Hybrid System ................................................................................................ 116
  9.6 Economic Conclusions ......................................................................................... 118

10 Environmental Impacts ............................................................................................. 121
  10.1 Batteries and the Environment ......................................................................... 122
  10.2 Hydrogen and the Environment ....................................................................... 124
  10.3 Energy Storage and the Atmosphere ................................................................ 127
  10.4 Environmental and Safety Conclusions ......................................................... 131

11 Conclusions ............................................................................................................... 133

12 Policy Considerations ............................................................................................... 143

References .................................................................................................................... 152
LIST OF FIGURES

Figure 1- Graph of Oil Prices over Time .................................................. Page 7
Figure 2- Demonstration of Intermittency ................................................. Page 9
Figure 3- Costs of Energy Sources ............................................................ Page 30
Figure 4- Demonstration of Potential Energy ........................................... Page 34
Figure 5- Battery Design ........................................................................ Page 39
Figure 6- Battery Arrangements ............................................................... Page 41
Figure 7- Fuel Cell Design ....................................................................... Page 51
Figure 8- Steam Reformation of NG .......................................................... Page 54
Figure 9- Electrolysis Basics .................................................................... Page 56
Figure 10- Chart of Hydrogen Efficiencies ................................................ Page 83
Figure 11- Chart of Hydrogen Efficiencies Overlaid by Battery Efficiencies Page 85
Figure 12- Graph of Space vs. Storage Capacity for Hydrogen and Batteries Page 97
Figure 13- Cost vs. Storage Capacity .......................................................... Page 111
LIST OF TABLES

Table 1- Carbon/Hydrogen Ratio of Fuels .................................................. Page 48

Table 2- Table of Hydrogen Efficiencies ....................................................... Page 83

Table 3- Data Used to Calculate Energy Density of Batteries ........ Page 93
ABSTRACT

This thesis examines two energy storage technologies, hydrogen fuel cell systems and electrochemical batteries, on the basis of their technological capabilities and their economic costs. The technological capabilities examined are efficiency, size, and performance abilities. These factors are used to determine which of the two technologies would be better suited in the implementation of a renewable energy system as the dominant energy carrier.

It is determined that while hydrogen is capable of performing several functions that electrochemical batteries cannot, batteries would be the optimal energy storage technology for the creation of a renewable energy system. The primary factor in this decision was the far superior efficiency of electrochemical batteries as compared to hydrogen fuel cell systems. Hydrogen was found to be superior in situations requiring large amounts of energy to be stored for extended periods of time as battery systems become far more expensive if they are used to store more than a few days worth of energy for the average American household, while the storage capacity of hydrogen fuel cell systems can increase with relatively little additional expense. The second area where hydrogen would be superior is in long distance / long running time transportation, such as buses, taxis, and shipping trucks. In these scenarios, hydrogen allows the driver to refuel the vehicle in a matter of minutes instead of the hours it would take to recharge a battery.

Hydrogen may find uses in other arenas than the two outlined but the end result of this paper is that batteries are the superior technology in the majority of the situations and hydrogen may only be used as an energy storage technology in those situations where electrochemical batteries are not technologically capable of performing a given task. Economically, hydrogen is better than batteries only in situations where large amounts of storage would be needed. Alternative methods of alleviating the need for storage should be examined before hydrogen is employed.
Chapter 1

INTRODUCTION

For the past century the human race has been harnessing the energy found within fossil fuels to generate electricity. While this has allowed unprecedented growth and rapid advances in technology, there have been associated costs to our current fossil fuel-based energy system. The dependence on and copious use of fossil fuels has lead to environmental, economic, and security threats that are significant enough that if any one of them came into full effect, our lifestyle would be drastically changed and human welfare could be at risk. Because these issues can be foreseen, there has been a great deal of attention and effort over the last few decades to move towards an alternative energy system that would not be subject to the same problems.

In order for an alternative energy system to improve on our current energy system, it must solve one or more, preferably all three, of the three issues: environmental impact, economics, and security. For a new energy source to solve the environmental problems caused by the current energy system it must be renewable and not cause significant damage to the environment through its implementation. The problems of economics and security are caused by the fact that fossil fuel energy is not evenly distributed throughout the world. This means that some people are net exporters of energy while others are net importers. A precarious situation has developed whereby our
nation has become highly dependent on a large steady influx of energy, and this energy, for the most part, comes in only a few forms and these are imported from a small number of locations. Small fluctuations in the supply of oil and natural gas can ripple outward causing all manner of economic instability, potential loss of energy service, and causing damage throughout our society. In order to solve these problems the new energy system must be available domestically.

There are a number of alternative energy sources that meet the requirements needed to solve the three issues with our current energy system. The two most commonly used of these sources, the two that have had the most development and are most commonly available in large amounts, are solar and wind power. The development and utilization of these sources has been hampered by a number of problems, including the problem of intermittency. Intermittency is caused when energy is provided by a system at times that are out of phase with the energy demands by the systems users, leading to insufficient energy at some times and an over abundance at other times. While it may be possible to reduce the effects of this problem by using a large number of diverse sources, one sure way to solve the problem would be to store the energy when it is being produced in excess for use in the times when insufficient energy is being generated.

In this fashion the storage of energy becomes an important issue as it offers a solution to one of the problems that is currently holding back the development of alternative energy sources that would solve the problems of environment, economics, and security caused by our conventional fossil fuel-based energy system. There are a number of different energy storage options that are available for utilization, however, two in
particular seem to be the most likely to be implemented in the near future: lead-acid batteries and hydrogen fuel cells. These are the most likely because they are the most technologically and economically developed and can both be used on a large or small scale without drastic changes in their efficiency, which grants them flexibility. Additionally they would be suitable for nearly all of the energy storage needs while other storage media could only be used in certain situations.

The purpose of this thesis is to examine these two energy storage options, lead-acid batteries and hydrogen fuel cells, in terms of efficiency, their technical ability, environmental impact, and expense in order to determine which one would be optimal for use in a newly developing energy system defined by an increasing reliance on renewable energy sources. These factors will then be applied to their potential uses in the fields of transportation, grid-connected energy storage, and stand-alone (not grid connected) energy storage. It will be determined if either of the two storage options can out compete the other in every area of the energy sector or if there will be some situations where one would be preferred and other situations where the other would be preferred and an attempt will be made to identify the situations where each would be the preferred technology. A final option to be considered would be if there would be any advantage to using both at the same time in a hybrid system that may be able to take advantage of the strengths of each. This data is intended to assist in the development of policies and incentives that will guide the development of our energy system so that the optimal technological choices are utilized to maximize the benefits of an alternative energy system, should one be developed.
Chapter 2
THE ENERGY PROBLEM

Decades have passed since it was first realized that human activity could be destructive and unsustainable, causing permanent harm to the planet and the life on it. The early calls for action were aimed at limiting the gross obvious pollution that was being caused by factories releasing effluent into the rivers and gasses into the atmosphere as well as similar types of point source pollution. These pollutants had immediate obvious effects and, since they were being released in large amounts from a few sources, they were relatively easy to control. But since that time a different type of pollution has become the focus of greater attention. The environmental problems that many environmentalists face today are not so easy to pin down and identify, nor is their solution as easy to come by.

Over the past few decades a new environmental topic has been rising to the forefront of activity and attention and that is global warming; the increase in the temperature of the earth caused by the rise of concentration of greenhouse gasses in the atmosphere. This rise is commonly accepted to be primarily caused by the burning of carbon based fossil fuels that release carbon dioxide and other byproduct gasses. (Byrne and Rich, 1992, 291) These greenhouse gasses collect in increasing concentrations in the atmosphere causing a greater retention of heat from the sun by the planet, which leads to
the gradual warmth of the Earth. The idea has been around for decades but when it was first broached as an actuality, as something that was occurring and that the effects of which would be seen in our lifetimes, the evidence supporting the concept was preliminary and many people remained unconvinced. The idea that humanity as a collective could that drastically change the atmosphere and our climate, which have remained unchanged by our activities in the thousands of years of recorded human history, was unprecedented and widely put down by both industry and government. But the evidence, especially in the last 15 years, has mounted and one by one critics have changed their minds and now nearly all of the active parties agree that some form of global warming is occurring, even if they don’t agree on the exact time scale for the event or how it should be dealt with. (Switzer, 2004, 289-290)

Another idea that has grown over the past few decades, since the 1970s (1973 to be exact), is that the price of our energy is far more volatile than we would like. The 1970s were marked by the energy crisis that was sparked by an oil embargo put into effect by OPEC. (See Figure 1) Oil prices rose and interest was sparked in developing alternative sources of energy to replace gasoline and oil as one of our primary sources of power. (Bernow, 1998, 776) The US government sponsored numerous efforts to develop cheap reliable mechanisms to draw power from sources that were available domestically, such as solar, wind, and ethanol. As oil prices stabilized in the 1980’s many of these efforts were abandoned or had their budgets cut, but the instability in the Middle East has continued to be a source of uncertainty for our energy security. In recent years especially, as the threat of conflict in the Middle East has increased and become open conflict in
several instances, the US government is renewing its interest in developing sources of energy that can be found within its own borders. (Dunn, 2002, 236)

Source: WTRG Economics

Figure 1- Graph of Oil Prices Over Time

Yet another situation that has come to light regarding our energy activities is that our supplies of oil and other fossil fuels, even without the instability in the Middle East, are limited. The concept of sustainable development argues that a society should not remove more from the environment than the environment can replace in that same period of time. The problem with fossil sources of energy is that they replace themselves very slowly compared to the rate at which we are extracting them, so slowly that they are considered to be non-renewable. The fossil fuels we currently rely on will quickly become increasingly scarce if we keep extracting them at the rates we have been.
This is a fact that is not disputed; the difference between experts today comes about regarding when we will finally run out of these fossil fuels. While it is difficult to get an exact date, many estimates show that we will have used all of the economically feasibly extractable oil within the next century and the same will occur for natural gas within the century after that. The only fossil source that does not seem to be in any immediate danger is our coal supply. Regardless of a person’s opinion on global warming, energy security, and even when exactly we will run out of fossil fuels, everyone accepts that someday the economical source of oil that is available today will run out and before that day comes an alternative source of power and energy must be developed.

When the three factors of sustainability, energy security, and global warming are examined together it can be of very little surprise that there is a great deal of activity in the alternative energy field today. While these efforts are still quite small compared to the conventional energy system, they are accelerating in both size and number and every year more governments are developing plans to shift themselves away from fossil fuels towards cleaner more sustainable sources of energy. Since the question of whether or not to develop alternative sources of energy is no longer really a question but is rather an inevitability, the focus of the debate today is what the new energy system should look like and when and how it should be implemented. There are dozens of plans that have been developed by different parties, many of which are drastically different from each other. The differences might be in the energy source (solar, ethanol, wind, biomass, clean burning coal, biogas, algae producing...
hydrogen, etc.), whether or not the energy should be produced centrally or locally, whether the plan should be forced through regulation or encouraged through market forces, and the list of possibilities goes on.

Many types of renewable energy sources are limited by a factor known as ‘intermittency’. Intermittency occurs when electricity is produced by a system at a time when it is not needed and not being produced when the electricity is needed. (See Figure 2. This is not actual data, simply a demonstration illustrating potential problems caused by an intermittent energy source.) Sources such as solar and wind are not available every hour when electricity is needed. (Anderson & Leach, 2004, 1) The sun shines during the day and never at night. The wind blows based on weather patterns that humanity has no control over. We cannot increase the amount of wind that is blowing when everyone

Source: Plurion Systems, 2008

Figure 2- Demonstration of Intermittency
comes home from work and turns on their air conditioning. Thus there may not be the power needed from these systems available when it would be used. This has been one of the reasons that these sources of energy have been limited in the role that they can play in our energy make-up. (Brower, 1998, 81) They have been used to displace some of the energy we get from conventional sources but they have not been able to fully replace them.

We do know, however, the average amount of power that can be harvested from these sources over a period of time and we know that, averaged across a long enough period of time these sources can provide enough total power to more than satisfy our current usage. The sun might not provide the energy we need at night, but it can provide more power than we use during the entire day when it is light outside, enough power for both day and night. The wind might be calm some days but over the course of a month it can provide enough power for that entire month, it will just be clumped together here and there, producing far more power than is needed at some times and not nearly enough at others. (Brower, 1998, 81) This is the problem of intermittency and one solution for this problem can be found in the realm of energy storage.

Storing energy is not a new idea, or even a human invention. There are many ways of doing it and examples of stored energy can be found all around us, in fact we are stored energy. We eat food and use the energy we gain from it when we want and as gruesome as it sounds our bodies contain a build up of potential energy that could be released through combustion, consumption, or decomposition. The universe and all life as we know it relies on the transference and storage of energy. Humanity has stored energy
for thousands of years in the form of grain harvested at one point in the year and saved to provide sustenance throughout the winter months. A closer example of the type of energy storage we wish to examine can be found in the damming of rivers or streams. This provides not just a stable water supply but also a controllable source of energy that can be released to power a water mill by opening a gate and releasing some of the stored water/energy that would have otherwise flowed by un-captured and unused by humanity. Instead this energy would be dissipated through entropy into heat, noise, and erosion; lesser energies that are harder to capture and of less use due to their lower potential energy.

All of our life is based around manipulating energies so that they are available when we want them and these energies all come from two sources, the heat from the earth’s core and the light from the sun. These constant steady sources of energy are the building blocks on which life exists, the sun supporting the photosynthesis that supports the base of our food chain and the core supporting a much more limited ecosystem of creatures, mostly microscopic, living in the deep seas around thermal sulfur vents where sunlight cannot reach. (Meadows, 1992, 45)

A more familiar view of energy would be in the ways humans have harnessed it that exceeds what might be considered natural. Water, wind, and biomass have been used for many centuries as a source of power but in the last few centuries a new form of energy has been used, fossil fuels. Fossil fuels are essentially the stored sunlight from thousands of years captured in organic material and then compressed into a high potential energy mass through time and pressure. These can be combusted to produce mechanical
or electrical energies when there is an energy demand. They are a highly stable energy storage system. But for the reasons described earlier, their use is limited by the rate at which they can replenish, which is essentially zero in the human time frame, and the effects that their use in large amounts has on the planet. Electricity can be produced directly from the sun and from wind (which is created by the sun) but electricity itself is difficult to convert into potential energy, or stored energy. But methods are available and it is on this subject that we at last come to the focus of the paper.

The storage system for electricity that is by far the most common and well known is the use of electrochemical batteries. These are found in different forms all throughout our everyday lives. Just from where I am sitting I can see a digital camera, a remote control car, a cell phone, a radio, a watch, an alarm clock, and a flashlight, each of which contains some form of battery that stores electricity; electricity that can be harnessed when the two contacts of the battery are connected through a circuit. Batteries use electrical energy to move electrons within the chemicals inside of them creating ions on each side of the battery creating a potential energy or stored energy waiting to be released as soon as a pathway is shown that it can flow through. When the pathway appears the energy flows through it and can be harnessed in the same ways that the original electricity that created the potential could have been used.

But batteries have a number of limiting factors. One problem, a problem that will be present in every storage technology due to the entropic laws of thermodynamics, is that through the process of storing the electricity in the battery and then removing it some of the energy will be lost. This is an efficiency loss. If you have ever felt a battery after it
has been used for a while or after it has been charged up you will notice that it is warmer
than it was to begin with. This is because some of the energy that was put in to or
removed from the battery was lost through the electrical resistance within the battery and
has been diffused as heat. That heat is energy that could otherwise have been used to
operate the cell phone, run the remote control car, or shine the flashlight had the battery
not been utilized for storage.

Batteries also contain chemicals within them that are highly toxic. Most batteries
contain warnings on them telling the users not to open them or break the seals because
the contents are toxic or caustic. They are often filled with acids that can seriously burn
flesh and even corrode metals. Batteries are even capable of exploding due to heat and
chemical reactions that can take place within them or when you try to recharge them.
(National Agriculture Safety Database, n.d., n.p.) There are battery recycling programs
but despite these efforts some of them end up in dumps where they can eventual break
open and their contents leak into the soil. Batteries are composed of highly dangerous
materials that are hazardous to human health and to the environment.

Another failing of batteries is that they are limited in the amount of energy that
they can store and the amount of energy that they can deliver at a given period of time.
As a battery charges it begins to develop a potential energy, or voltage, that acts in
opposition to the voltage that is charging the battery. As more charge is placed into the
battery this opposing voltage grows and energy enters the battery more slowly until the
opposing voltage finally reaches the level of the charging voltage and the charging is
reduced to zero. The rate at which the opposing voltage grows in comparison to the
amount of energy that is stored in the battery is a result of the capacitance of the battery. Some batteries have a higher capacitance than others and thus can store more energy, but every battery does have a limit. Once a battery is fully charged by a voltage source, more charge could be placed into the battery by an even higher voltage, but the opposing voltage would just grow to the level of this new voltage and then stop once again. This could continue indefinitely except that at a certain point the barrier that keeps the charge from flowing across the potential within the battery would fail. (Serway, 1997, 749)

Everything that has a capacitance has a voltage that, if it is exceeded, the electricity will arc across the separating barrier and short out the battery, eliminating some or all of the stored potential energy. Such arcing usually destroys the battery, possibly causing it to explode or leak its dangerous inner materials. (National Agriculture Safety Database, n.d., n.p.) It is this intrinsic property of batteries that limits the amount of energy that can be stored within them and also explains why different batteries must come in different sizes and shapes in order to supply different levels of energy. Size is often a factor for how much energy can be stored within a battery (which is why a car battery is so large and the battery for my flash light is so small) but it can also be affected by the material component from which the battery is made. More advanced modern batteries are constructed differently than early batteries and thus can hold more energy in a smaller size, but they too are limited in the amount of energy that can be stored within them.

Batteries are also limited in the amount of energy that they can produce over a given period of time. This is due to mechanical/electrical factors within the battery that
prevent too much electricity to flow from them. A number of small batteries could be put in series to create a 12 volt battery, which is the same voltage as a car battery, but if the two ends of this constructed battery were connected there would be no visible effect, unlike if the two leads of a car battery were connected in which case there would be sparks and a great deal of heat would be released. Even though the batteries were of the same voltage the energy that they could put out was limited. This limiting of energy flow from a battery puts boundaries on what it can be used for.

Some of these shortcomings could be partially overcome by simply adding more batteries, but the problem with that solution is that batteries can be quite expensive as larger numbers are needed. The materials, the labor, and the disposal costs for the battery are all significant for the amount of energy that can be stored within them. Even rechargeable batteries will eventually fail and need to be replaced, and many rechargeable batteries cannot be drained below a certain level of their stored energy without being damaged. The number of batteries that would be needed to store the amount of energy that would be needed to solve the intermittency problem represents a huge initial cost and their replacement over time is a significant continuing cost that needs to be accounted for.

As was mentioned earlier, batteries are only one way in which energy can be stored and while they may currently be the dominant form of electrical energy storage in renewable energy systems, they may not be the best way. An alternate form of storing energy would be through the creation of hydrogen. An initial energy source, such as solar or wind power, could be used to create hydrogen and that hydrogen could be stored until
electricity was needed at which point it could be run through a fuel cell in order to create electricity. Like batteries, hydrogen will be subject to problems of energy storage, costs, potential environmental issues, and efficiency issues, but could it represent a more likely candidate for renewable energy storage systems than conventional batteries? The remainder of this thesis will examine this issue by comparing and contrasting the two storage media to determine the strengths and weaknesses of each to determine which is technologically, environmentally, and economically dominant, especially as they would apply to the development of a sustainable alternative energy system.

In addition to determining the strengths and weaknesses of the two storage media, this data should be used to help develop a set of policies that guides the development of a budding energy infrastructure onto the path that would best accomplish the goals of improved environment, economics, and security, or at least the best combination of these factors if a compromise must be reached. These policies need to be designed to compensate for the failures of the market to fully pursue the same goals as we might desire due to distortions that change the course of market development to cleave more closely to the interests of a particular industry, interest group, or individual. Optimally our goals could be achieved through market forces, but unless the market itself is changed to take into account issues such as security and environment, then the current market will not work for these goals. This thesis will seek to provide information that will help to guide the formulation of future energy policy.

The policies to be used could be incentives for the preferable technologies, money for further research and development, and educational programs. These would help to
spur growth for a field that might not yet be economically competitive with the current system yet, as is the case for renewable energy. The market itself could be changed by attempting to make industry responsible for the full environmental effects of their actions rather than placing many of these costs on the shoulders of the tax payers as a whole. Even though, if these costs were assumed by the corporation instead of the taxpayer, the taxpayer would end up having to carry these costs as the industry passed them along to their customers, it would begin to send out the proper market signals.

If the cost of electricity increased to account for global warming damages instead of taxes increasing to pay for global warming damages then the customers would be less likely to undertake activities that would cause global warming. Those who didn’t partake in worsening global warming would be rewarded monetarily and thus the right signal would be sent out and the damage might be prevented in the first place. Without those market signals, however, all of the taxpayers pay the same whether they produce more or less greenhouse gasses and they receive no reward for taking environmentally safe actions.

A final route that the government could take to develop an energy system that would accomplish the three goals of environment, economics, and security would be in the assistance in developing the necessary infrastructure needed to have a fully developed and productive industry. While this could develop naturally within a market, it would be quicker with government assistance and funds. Either through public-private cost share programs or bulk procurement agreements, the government has the resources needed to give an industry a huge head start and guide it through the beginning stages.
While it is necessary to obtain the knowledge regarding the optimal energy storage technique for each option, this knowledge is of little use unless there are methods in place to guide the industry towards this goal. By examining what system of energy production would be optimal for our goals, we can also begin to determine what actions will need to be taken to achieve this end. The policies that the government can put into place have a level of power comparable to the technological capabilities and market forces in how strongly they can affect the outcome of a developing energy system.
Chapter 3

THE DEVELOPMENT OF DECENTRALIZED POWER PRODUCTION

The idea of providing power on site to fuel machines rather than having to import power from a central source has been around for thousands of years. Evidence of this sort of thinking can be found in the ancient windmills and watermills that have been used to grind grain, run saws, and accomplish other heavy labor for hundreds if not thousands of years. Windmills have been found as far back as ancient Persia more than a thousand years ago. (Flavin, 1999, 4) These ancient sources of energy were, ironically enough, both renewable and decentralized sources of power, and for hundreds of years they were the only source of mechanized power.

When the industrial age struck, these sources of power began to fall into disuse. Soon steam power was running the larger machines and it could even be used as a mobile source of energy for transportation. The steam engine was more versatile than wind and waterpower as it could be used at any location, could be made mobile, and was a more controlled source of energy. Steam was the source of power for the beginning of the industrial age and humanity’s history of reliance on fossil fuels. (Schobert, 2002, 566-567)
3.1- Past to Present

3.1.1- Rural Beginnings

As the electrical age began, around the turn of the 20th century, wind power was used to produce electricity. It was used for this purpose as early as the 1880’s but electricity was also being produced in large coal burning plants and wind simply did not have the ability to compete with the centrally produced electrical power. (Schobert, 2002, 566-567) Because of the low cost and the overall superior reliability of electricity from coal, wind was relegated to use in locations where electrical lines from the power plants could not reach. In the rural parts of the United States wind was often the most economical source of energy and it was used to power the small amount of electrical equipment that a farm owner might own. But once again the industrial age caught up with wind power through the rural electrification program and as more and more farms were able to receive their electricity from central power plants, the electrical windmill became more of an icon of the American heartland than a commonly used power source.

3.1.2- Energy Crisis

The progress of large centralized power plants continued unhindered up until the 1970’s when the United States suddenly found itself in an energy crisis. The 1973 Oil Embargo caused the price of oil to skyrocket and the nation faced rising costs of energy on all fronts. For roughly a decade, beginning with the Oil Embargo, the government attempted to find alternative sources of energy to reduce their dependence on foreign oil.
By this time, photovoltaic cells had also been developed and the government at both the state and federal level began to provide financial incentives to promote the use of these alternative energy sources, sources that were available domestically. (Bernow, 1998, 376) The goal of these incentives was to make these alternative sources of energy more cost competitive with conventional energy sources so that a market and an industry could be developed for them that would begin to take the load off of the conventional power system.

The incentives offered were nearly all financial in nature, although some were regulatory. These incentives tended to be tax breaks for the initial purchase of alternative power systems. The federal government provided up to 25% of the purchase price of the system as a tax credit (Harvard Business School, 3, 1993) and certain states also offered large tax credits. The largest of these was a 50% tax credit that was offered by California. (Dodge, n.d., n.p.) The end result of these purchases is that investors were able to recoup as much as 75% of their initial capital within a year. Even though no particular technological breakthrough had been made, the price of wind and solar power (which are primarily dependent on the initial cost of the systems since they require no fuel to be purchased) artificially plummeted and wind and solar farms were constructed in many areas of the US in unprecedented numbers, especially on the west coast.

3.1.3- PURPA

Even with these large tax credits, which dropped the price of alternative energy systems to the point where they were economically competitive with conventional
energy, the movement to develop these alternative energy systems would not have been possible without a particularly important piece of legislation within the alternative energy field. In 1978 the federal government passed the Public Utilities Regulatory Policy Act (PURPA), legislation that forces utilities to allow independent power producers to tie into the electrical grid, thereby giving alternative energy producers access to electricity customers. Additionally, the act requires the utilities to purchase the power that is produced by alternative sources at the price that it would have cost them to make that power themselves. (Bernow, 1998) The PURPA legislation not only allowed independent power companies to feed into the electrical grid but it also permitted individuals to connect alternative energy systems to the electrical grid though a process known as ‘net metering’.

Net metering is defined as a financial crediting system for the net energy produced by qualifying forms of power production onsite at homes or business. Individual systems are connected to the electrical grid, feeding power that is metered directly into the common electrical grid and then subtracted from the watt-hours supplied by the grid to the home or business. In principle, the source of the power could be anything but in practice net metering laws are designed to promote renewable, green sources of energy such as wind or solar. The effect of connecting this sort of system to the grid is that each kilowatt-hour of energy produced by the qualifying system, rolls back the metered usage. (EERE, n.d., n.p.) Thus, a house that uses 50 kilowatt-hours each day but has a system that produces 20 kilowatt-hours on average, only pays the electrical utility for 30 kilowatt-hours of electricity. If an individual system produces more power
than is used in a given period of time the customer may even be paid by the electrical utility for this excess power generation, although this, like many aspects of net metering, is determined by state policies which differ across the country. (Starrs, 1996, 9-10)

### 3.1.4- Crash in the 1980s

The relative success that the alternative energy business enjoyed beginning in the mid-1970s slowed significantly in the mid 1980s. Nearly a decade after the boom had begun it ended. People’s fears that had arisen due to the energy crisis faded away as oil prices fell and then stabilized. As the laws and statutes that granted the tax incentives for alternative energy came up for reevaluation and renewal, many were allowed to expire in favor of other uses of state money and the public seemed to lose interest in alternative energy. (Switzer, 2004, 175)

When the incentives disappeared, the alternative energy market found itself in a precarious position. It had grown and developed depending on the support that the incentives gave and with that financial crutch removed, (Danish Wind Association, 2003, n.p.) growth in alternative energy capacity dropped. (Bernow, 1998) This slowing of market development damaged the long-term capability of investment in the alternative energy market, as many people were now wary of what they viewed as a volatile market.

Since this crash has occurred, alternative energy systems have been steadily improving technologically, especially in the wind industry. Not only have the technical aspects of the systems improved, leading to smaller, higher efficiency, more reliable units, but the costs for these systems have dropped as well so that they are more
competitive with the conventional energy system. Throughout the 1990s the alternative energy market improved and it now seems to have regained its earlier momentum. Once again, the United States is interested in developing alternative energy systems, due to increasing insecurity in the Middle East and due to the rising concerns over global warming. Now that the technology has improved and can stand on its own without being unduly propped up by a large incentives scheme it seems to be on much more stable ground and is steadily growing.

3.2- Current Applications of Decentralized Power Production

Where does this put decentralized power production today? What role is this technology able to play in the larger picture of our electrical market? There seem to be four main uses for alternative energy, three of which are decentralized and one of which is a centralized system. The centralized system is the role of the independent power producer who sells electricity with a green label on it. The other three uses, which are decentralized, are net metering, peak shaving and load shaping, and rural electrical services. (Dell and Rand, 2001, 6)

3.2.1- Rural Electrical Servicing

The simplest of these applications is that of rural electrical servicing. This is essentially the same role that wind originally played in the American farmland. Some locations are quite remote or their users are mobile. Examples or remote areas might be a village in the middle of the Amazonian jungle or a small island nation. Decentralized
power production is even used for certain nomadic peoples who need to be able to carry their power source around with them, such as the nomads of the Mongolian regions of China. (Byrne, 1998, 45) For these people, decentralized power production may be the only option that is technically or economically feasible to them. Rather than running and maintaining miles and miles of power lines through the jungle or along the sea floor, it makes far more sense to just produce the power on site at less expense. This is obviously less of an issue in the United States where the vast majority of areas have a connection to the electrical grid.

3.2.2- Green Energy Production

With the deregulation of the electrical industry occurring and with many consumers now being offered a choice of utilities, many people now wish to show some support for the environment by buying electricity that has been produced in a ‘green’ manner, meaning that it was produced without emitting toxic or greenhouse gasses and without causing undue damage to the environment. While the customer does not actually use the specific electricity produced in a green manner, they do pay a premium to have an amount of electricity that they used produced in a green manner and fed into the grid so that the overall amount of electricity produced in a way that would negatively impact the environment is reduced. This green energy is usually produced at a central location either by the utility or by an independent power producer. (American Wind Energy Association, n.d., n.p.)
3.2.3- Net Metering, Load Shaping, and Peak Shaving

The final group of the current applications for alternative energy systems is net metering and the associated peak shaving and load shaping. Net metering, as explained earlier, involves producing power at one's home or business and feeding it back into the grid, essentially crediting you for that energy when the time comes to pay your bill. The laws governing what type of system is allowed for net metering, how any excess generation is handled, and how many people within the state can hook up to the grid varies widely from state to state but they all share the same basic idea. (Database of State Incentives for Renewable Energy, n.d., n.p.)

Peak shaving and load shaping are more advanced styles of net metering, up until this point net metering systems simply have been feeding the electricity they produce into the grid whenever they happen to be able to produce it. The owner gets the electrical credit whether the power was produced in the middle of the night when none was being used or at the highest level of use during the day. In peak shaving and load shaping the owner of a distributed energy system stores the power that is produced and feeds it into the system when the electrical demand for the building or complex is at its highest. This approach cuts a user’s peak demand by the amount of energy being fed into the system by the distributed energy system. (Byrne, 1997, 147-150) A building that uses 300 kilowatt-hours per hour all day except from 4pm-5pm when it suddenly needs 500 kilowatt-hours for that hour might be able to provide 100 of those kilowatts for that hour from energy they have produced and saved with their decentralized system. This means that the
maximum amount of power that the utility will ever have to provide to the building is 400 kilowatt-hours per hour instead of 500 kilowatt-hours per hour.

This is a valuable service for many reasons. First, a utility has to have enough capacity to satisfy the maximum amount of power needed at any given time. If the maximum amount of power needed during the relatively short peak can be reduced then the utility will need less overall capacity to provide the electricity that is needed. Because it is the peak amount of electrical demand that determines the amount of capacity a utility needs, peak power costs much more than off-peak power (this higher cost is sometimes reflected in a monthly price based on their peak power demanded in addition to their total power used). (Byrne et al., 1995, 2) These two factors make the cost of having a high peak compared to the average power usage very expensive. Peak shaving and load shaping are designed to reduce a building’s load on the electrical grid and, ideally, attempting to level out hourly power usage. This service can be accomplished by storing the power produced by an onsite source and feeding it into the building’s electrical system when it is needed. This is quite possibly the most cost effective use of alternative energy sources currently available as it reduces the production capacity needed by the utilities and it reduces the amount of money owed to the utilities due to a high peak power demand.

3.2.4- Summary of Current Decentralized Power Uses

With the exception of rural electrical services, each of the types of electrical service that decentralized power production commonly provides fills a fairly small role in
the overall power structure of a community. There are no utilities that allow more than a small percentage of their power supply to be made up by net metering. Load shaping and peak shaving do not attempt to replace their power supply with alternative decentralized energy, they simply try to reduce the amount of electricity used at the most expensive times; overall a small fraction of the total electricity used is displaced in that scenario, though peak shaving and load shaping do have the capability of slowing or ending the growth of centralized power development. Even in the alternative energy system that is centralized, the independent power producer selling green energy, only produces a small amount of the total energy that is produced by a region. For the most part, decentralized alternative energy systems have been limited to the sideline, their role limited to an accessory to the overall electrical power system, which has operated in essentially the same manner since it was developed at the turn of the 20th century. (Bernow, 1998, 376)

3.3- The Current Limitations of Decentralized Generation

There are two main factors that present themselves as obstacles keeping alternative energy projects, centralized or decentralized, from accounting for a significant portion of our total electrical production. These two factors are expense and intermittency. This pair of problems are areas where the conventional energy system has historically performed better than the alternative energy sources and are a large part of the reason that alternative energy has not been able to take on more than a supplementary role within our energy structure. As of late, however, these two obstacles have been swayed by possible solutions.
3.3.1- Higher Costs of Production

The problem of expense has always been a tricky issue and this is because there are so many different factors that could be considered that can drastically change the perceived and real costs of both alternative and conventional energy systems. In terms of evaluating the cost of the conventional energy system, which has a record of being able to produce electricity at a cost of 2-3 cents a kilowatt-hour (Schobert, 1999, 578-579), the primary change that can occur is whether or not the electricity is being delivered to the customer at the true cost or if the price consumers pay is determined only after the true cost has been warped by market distortions or by only a partial tallying of the true costs.

There are a number of market distortions that can occur in the conventional energy system that artificially lower the cost of electricity. (Dunn, 2002, 238) These are present in the forms of large government subsidies and tax incentives. Essentially they are plans that help to support the electrical industry and ensure cheap electricity for the citizens. They have the net effect of making conventional electrical sources seem cheaper than they truly are, however, and by comparison makes alternative sources seem more expensive. (Geller, 2003, 38)

The other half of the price distortion has to do with the manner in which the industrialized world has commonly tallied the costs of its activities. Through the current market structure a company only examines and is only responsible for the direct costs of accomplishing their goal. In the electrical industry this might include the costs to the mining company to purchase the land and then the cost to mine the coal out of the land
and transport it to the power plant. Then, of course, they would take into account the costs of running the plant and distributing the electricity to the customers.

What they fail to factor into the equation are the indirect costs that will be a burden on society as a whole but do not have monetary costs that the company is responsible for. Examples would be increased flooding due to the mining operation and the costs of the air pollution that will decrease air quality and cause global warming. Some of these factors are much easier to account for, such as the costs of the increased flooding, but something like the cost of decreased air quality is far more nebulous. It may cause an increase in asthma and lung cancer or is might simply reduce aesthetic values by reducing visibility in scenic areas. Trying to calculate and factor these costs into the overall costs of a process is a movement known as environmental, or ecological, economics. (Hohmeyer, 1992, 142-143)

Source: Exxon Mobile

![Costs Converging Though Wind, Nuclear, Solar Remain Higher Cost for Power Generation](image)

Figure 3- The Costs of Energy Sources
To obtain the true costs of the conventional energy system the subsidies and incentives would have to be removed and the entire process would have to be viewed through a lens of environmental economics. If this were done then the price of electricity from conventional sources would increase and by comparison the alternative sources would seem less expensive. (Hohmeyer, 1992, 165) While there might be a significant amount of argument regarding the specific costs of various environmental effects or what should and should not be factored into the true cost, the overall effect on the cost of conventional energy would not need to be large for the price of alternative energy sources to be competitive with that of the cheapest conventional power source, coal.

The effect would not need to be large is because the cheapest of the alternative energy sources is already very close to being competitive with the conventional energy system. Wind energy currently can cost as little as 4 cents a kilowatt-hour, and that price can be expected to continue dropping as the economy of scale increases and technological improvements occur. (See Figure 3) While other alternative sources are not so close to competitiveness with conventional energy sources, the removal of the market distortions, accounting for the environmental and social costs of the conventional energy system, creating an economy of scale, and further technological improvements would almost certainly combine to make alternatives a cheaper source of energy than the true cost of our current energy system.
3.3.2- Intermittency

While a solution is visible for the problem of cost, the issue of intermittency is slightly more difficult. A solution is visible, but may itself be difficult to obtain. As was mentioned before, the issue of intermittency is one of the energy being produced at the wrong time, or even more specifically, the energy production occurring on a schedule that is either unpredictable or predictable but out of phase with the cycle of when it is needed. (MacKenzie, 1992, 42) The conventional energy system is both predictable and in phase with the electrical demand because its production schedule is completely determined by the plants operators. The plants can be turned on when power is wanted, add more or less fuel as demand changes, and the production matches the demand rather neatly. There is not the same level of control for the wind or the sun, however.

This particular problem for the alternative energy system can be dealt with because it can be determined the total amount of energy that will be produced over the course of a year within a reasonable degree of accuracy. It can also be determined a reasonable estimate of the monthly power production from these sources. This is because over a given period of time the average amount of sun or wind an area receives is nearly constant from year to year.

How does this of assistance, however, if this energy is still coming in out of phase with the energy demand? The average demand is also fairly well known over a period of a month or a year. If it is known how much energy will be needed over a period of time and how much is available over that same period of time then enough alternative energy generating units could be erected to capture that much of the available energy. All that
would have to happen then is for that energy to be distributed when it was needed. To
accomplish this there needs to be a way to store it, and storing something immaterial, like
electricity, can be a little complicated.

With a good way of storing electrical energy it would be possible, at times when
more electricity is being produced than is demanded, to meet the entirety of the demand
directly from the alternative energy sources and take the remainder of the production and
store it. When the demand for electricity is higher than the system can produce, then the
entirety of the current production could go towards satisfying the demand and the
remainder of the demand could be met by the electricity that has been stored from when
production was greater than demand. If the average production for a month is higher than
the average demand then the electrical needs should always be able to be met through a
combination of stored energy and direct production.

There are literally hundreds of ways that the energy from electricity could be
stored and a number of them have been used over the course of history. The excess
electricity could be used to raise weights into the air or pump water into cisterns on the
roofs of buildings and then the weights could be allowed to fall or the water be allowed to
run down, powering generators as they fell to the lower potential state of energy. Due to the laws of physics the energy used to place them at the higher levels of potential energy (in this case increased height) could be recovered and used for work (electrical production) as they returned to their lower states of potential energy. (Serway, 1997, 202-203) (See Figure 4) Other similar examples could involve large spinning disks, swinging pendulums, compressed springs, wound up springs, and so on. All of these devices can be used to store energy in the form of mechanical potential and have been used to do so in power plants, watches, clocks, and other devices. But when these devices are used in the storage of large amounts of energy they tend to be large, inefficient, and difficult to maintain due to their mechanical nature. If a person wanted to dedicate their basement to a giant weight that would raise and lower, storing and releasing energy, then they certainly could but size and cost might provide significant obstacles to that course of action.
Luckily, there are other options for the storage of energy and the purpose of this paper is to examine the merits and flaws of two of those options, as they would apply towards the overall goal of implementing a decentralized alternative energy system. One of these technologies is already well established and has been used for nearly as long as, or even longer than, electricity has been commercially produced. The other is a technology that has been around for several decades and, despite some recent attention by the media, government, and public at large, it has largely remained a technology used for only a few specific purposes and in academic and governmental studies.

The technologies are, of course, the electrochemical battery and the fuel cell. Unlike the other examples given, these two technologies do not store the energy from electricity through mechanical means. Instead they use electrical and chemical properties to store the electrical potential. This allows them to have few or no moving parts and also allows them to be smaller and less dangerous than mechanical potential energy could be. The electrochemical nature of these devices also allows them to avoid many aspects of the specter, friction, which can greatly reduce efficiency.

3.3.3- Other Limitations

In addition to the technical and economic problems that stand in the way of decentralized power, there are additionally a number of political and social blocks that would stand in the way of the development of a decentralized power system. Much of the problem is in the issue of inertia. For decades our society has been pushing forward with a strong centralized power industry and a great deal of business and infrastructure has
been built up around the concept of centralized power. Everything from the coal mines to the power plants to the utilities and the transmission lines as well as countless other areas of the industry have had a lot of time, effort, money, and research placed into their development and because of this there will be a large amount resistance to abandoning the system.

In addition to all of the stranded capital that would be left behind, there would also be a question of the people left behind who currently work in this industry and may not be able to transition over to a new job. New jobs would be created for the development and maintenance of the new decentralized system, but they would not necessarily be jobs that someone who worked in the original power industry could transfer over to. A coal miner, for example, may not have any utility for his skills within the new power structure.

In addition to abandoned capital and an abandoned work force, there would be a shifting of resources that might be opposed by those who currently feel as though our situation benefits them and that the new situation would not. Areas that are currently rich in resources like coal, oil, or natural gas and have a great deal of industry set up in the exportation of those goods would not want to see their current customers become energy independent (as would be needed to achieve the goals of energy security and improved economics). As a result they would lobby strongly within the government for support to the old system, the system that benefits them rather than supporting a move to a new system that no longer requires their neighbors to import energy from them.
In addition to the technical and economic issues that would be associated with the shift to a new energy system, there are a large number of these other issues that are not problems within the new energy system itself, but instead are reasons that the new system would be opposed for social and political reasons. Because the shift from one energy system to another is so large, there is bound to be much shifting of power within governmental entities and industries and also a large number of changes in the skills needed within our work force. All of these changes may be opposed by the people who are benefited by our current system, regardless of the benefits that the new system could provide to the world at large.
Chapter 4

HISTORY AND DESIGN OF ELECTROCHEMICAL BATTERIES

Batteries as a source of power are extremely common in the world today. Many of devices that are used every day require batteries to operate and in a world where electronics are increasingly becoming smaller and mobility is more of an option they will only increase in demand in the near future. Watches, flashlights, cell phones, cars, and many other devices rely on batteries to operate in the convenient and mobile fashion to which we have grown accustomed and yet the average person probably has no idea how they operate or even the limits that are imposed on them. Today the world of batteries is expanding as new technologies are designed to fit increasingly demanding roles in our lives.

![Battery Design Diagram]

Figure 5- Battery Design

The earliest batteries were available in the 1800’s, (Dell and Rand, 2001, 10) before electrical generators were even available. The first of these was designed in 1800 by Allesandro Volta and consisted of plates of zinc and silver separated by paper soaked
Another battery that was invented before the use of generators was the Daniel cell, which was completely stationary because it relied on the gravity separation of two different sulfate liquid in each of which was suspended a different metal plate. (See Figure 5) These early batteries operated on the same principles as our modern batteries do now, over two centuries later.

The basic concept of the battery is that two plates or rods of different metals are separated and immersed in an electrolyte, or a substance capable of passing electrons. Ions (positively or negatively charged atoms and molecules) are formed at the two different plates and that creates an electrical potential. Laws of electrodynamics dictate that there will be an attraction between oppositely charged particles so the extra electrons that make the negative ions negative are pulled towards the positive ions along the path of least resistance. When the two plates are connected through a circuit the electrons flow through the circuit to neutralize the ions and complete the chemical reaction. (Faissler, 1991, 22) This passage of the electrons is electricity.

The setup described above is called a cell. A cell consists of the two metals and the electrolyte and has a set amount of voltage and a set amount of current that it can produce. The voltage and the current that can be produced depend on the metals used, the electrolyte, the size and shape of the metal plates, and the general configuration of the cell. Each combination has different characteristics and some that are good for certain applications will not be good for other applications. (Griffiths, 1999, 104)
Different voltages and amounts of power can be obtained from batteries by using more than one cell in an arrangement called a stack. (See Figure 6) There are two basic ways to combine cells in a stack formation; they can be placed together in series or in parallel. When they are placed together in series it is the same arrangement as when you put batteries into a flashlight. They are placed end on end so that the negative node of one battery is connected to or contacting the positive node of another battery. A series arrangement could have as many cells placed together positive node to negative node and the net effect is that the voltage potential of each cell adds together so that the stack has a voltage equal to the combined voltage of cells. The current that can be produced, however, does not just add up, instead it will produce the amount of current that any one of the cells would on its own. (Serway, 1997, 798)
The alternative way of arranging batteries is to place them in parallel. This means that instead of connecting the positive end of each battery to the negative end of the next, all of the positive ends of the batteries are connected and all of the negative ends are connected. In this arrangement the combined voltage does not increase over that of the batteries but the overall current that it can put out increases to the sum of the current the batteries can put out over a given period of time.

These rules are simplified versions of the actual rules of electronics governing sources of electrical power connected in series and parallel. They will, however, suit the purposes of this thesis, the reader should just be aware that when batteries with different powers and voltages are combined the results will not be exactly as described above. For the systems that will be examined later in this paper, however, the battery stacks should contain all the same type of battery.

The type of battery that we are interested in is the lead-acid battery, or more specifically, deep-cycle lead-acid batteries. Lead-acid batteries are the types of batteries that are typically used as car batteries. They are used in most kinds of vehicles and for a variety of other purposes as well. The reason that they are used for these purposes is two fold. To begin with they are capable of providing a large surge of current in a short period of time and this is needed to start most vehicles. The second aspect that makes them extremely useful is that they are capable of being recharged when a potential is run in the opposite direction than electricity would normally flow from the battery. This is what occurs when a car is jumpstarted after the battery has run down. The process is also
constantly occurring after you have started up your car, the alternator recharges the battery, replacing the stored energy that was used to start the car.

The chemical reaction that governs lead acid batteries takes place between lead (Pb), lead dioxide (PbO₂), and a strong sulfuric acid electrolyte (H₂SO₄ and H₂O). The following reactions occur within the battery:

\[ \text{Pb} + \text{H}_2\text{SO}_4 \rightarrow \text{PbSO}_4 + 2\text{H}^+ + 2\text{e}^- \]
\[ \text{PbO}_2 + 4\text{H}^+ + \text{SO}_4^{2-} + 2\text{e}^- \rightarrow \text{PbSO}_4 + 2(\text{H}_2\text{O}) \]

The two electrons that are freed during the reaction on the lead plate travel across the circuit to be present for the reaction that occurs at the second plate, thus generating the voltage. The net result is that lead sulfate (PbSO₄) builds up on both plates and the acid is continually diluted with water. The reaction would stop occurring when the lead or the lead dioxide was completely and impenetrably coated with lead sulfate. (Kotz, 1999, 979)

The lead acid battery reaction produces a little over 2 volts for each cell. Thus six cells are placed in series to make up the classic car battery. These batteries are rechargeable because the components of the initial reaction remain present at the site of the reaction. This means that if an electrical current were placed in the opposite direction the reaction would occur as such:

\[ \text{PbSO}_4 + 2(\text{H}_2\text{O}) \rightarrow \text{PbO}_2 + 4\text{H}^+ + \text{SO}_4^{2-} + 2\text{e}^- \]
\[ \text{PbSO}_4 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{Pb} + \text{H}_2\text{SO}_4 \]

Thus the exact same components are returned in the reverse reaction. This cycle of charge and discharge can occur many times under the proper conditions.
The difference in car batteries and deep cycle batteries has to do with differences in their physical design, since the chemical reactions involved are exactly the same. A car battery needs to be able to put out a lot of power in a short period of time when the car is started. The amount of power in an amount of time is governed by how quickly the chemical reactions can occur. Each individual reaction takes place in the same amount of time but car batteries are designed so that more of these reactions can take place at any given time. This is accomplished by making the lead and the lead dioxide plates very thin and spongy so that more of their surface area is exposed to the electrolytes. (Kotz, 1999, 979) This design allows them to put out a lot of power, but it also makes them easier to damage. This type of battery is not designed to be deeply drained because the thinner plates become delicate as the lead sulfate replaces their original material and they can become permanently damaged if they are frequently excessively drained.

A deep cycle battery, however, is far less susceptible to damage through constant draining and recharging because the lead plates used are thicker than those in car batteries. This means that they cannot put out a lot of power in a given period of time but it makes them far more stable. Deep cycle batteries are the kind used in renewable energy systems today because the system is far more useful if you can drain a larger amount of the stored power (when you need it) and then recharge it hundreds of times. The car battery design simply couldn’t withstand the frequent heavy charge-discharge cycles that deep cycle batteries have to go through to perform the function of supplying electrical energy in a useful manner. (Dell and Rand, 2001, 10) The down side is that deep cycle batteries have a much lower maximum current (power per unit of time) but short periods
of high currents are not needed as often in renewable energy systems and if a high current is needed over an extended period of time then a number of deep cycle batteries can be placed in parallel.

It will be these systems of deep cycle batteries that will be the focus of comparison for the remainder of the thesis since they are the only batteries which have been seriously entertained as being a part of a renewable energy system and which have classically been used in tandem with distributed renewable energy systems everywhere from peoples back yards to trailers to out in the Amazonian rainforest. For the remainder of the paper, references to batteries relate to deep-cycle batteries unless otherwise stated.
Chapter 5

HISTORY AND DESIGN OF HYDROGEN AND FUEL CELLS

The basic concepts of the hydrogen fuel cell have been known for decades, but their first common use was for the NASA space program where they are used to provide electrical power for the vessels, as well as some water. Fuel cells are often considered to be the future of energy and people have not only envisioned, but have actually placed, them in everything from buildings to cars to laptop computers as the source of energy.

Fuel cells run, at their simplest, fueled by pure molecular hydrogen, $\text{H}_2$, in gaseous form. Hydrogen goes into the fuel cell along with oxygen and all that comes out are pure water and electricity. (NAS, 2004) This seems, from the initial description, to be the next best energy source after cold fusion, but this is also the process being described in very simple terms. As more is discussed about the hydrogen fuel cell apparatus and what goes into making it work, hydrogen and fuel cells will rapidly seem more complicated and may not seem like such a clear choice.

5.1- Decarbonization

Using hydrogen as fuel has been a trend that has been approached since the beginning of fuel usage. This trend is known as decarbonization. The carbon to hydrogen (C-H) ratio for fuels has been steadily decreasing. (Dunn, 2001, 88-89) Wood and
biological fuels have a higher C-H ratio than coal, and coal has a higher C-H ratio than oil and gasoline, and gasoline has a higher C-H ratio than natural gas (methane). Hydrogen has the lowest possible C-H ratio possible, having no carbon at all. (See Figure 7)

Source: Dunn, 2001

<table>
<thead>
<tr>
<th>Substance</th>
<th>Carbon : Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>10:1</td>
</tr>
<tr>
<td>Coal</td>
<td>2:1</td>
</tr>
<tr>
<td>Oil</td>
<td>1:2</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>1:4</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>No Carbon Content</td>
</tr>
</tbody>
</table>

Table 1- Carbon/Hydrogen Ratio of Fuels

There are several benefits to having no carbon present in a fuel. Primarily, it is cleaner to use as a fuel than substance with high carbon content. Two of the main pollutants that result from our current fuel use are carbon monoxide (CO) and carbon dioxide (CO₂); both are greenhouse gases. Obviously these gases cannot be produced if there is no carbon present to form them. Thus the fuels we have been utilizing have been progressively getting cleaner and cleaner, in regards to carbon content, leading to this ultimate, carbonless fuel that has no emissions whatsoever other than water.
There is one major problem with hydrogen, however. It cannot really be considered a source of energy because unlike oil or coal, there are no large natural deposits of molecular hydrogen on the earth, nor is it naturally produced in any large amounts. Despite being the most abundant element in the universe, there not large quantities of pure hydrogen available for use on the planet. Instead, it is almost all tied up in other molecules, such as in organic matter, fossil fuels, water, and numerous other substances and it cannot be used in a fuel cell in this form. (Dunn, 2001, 98; NAS, 2004) In this sense, hydrogen cannot be considered an energy source.

Instead, hydrogen can be considered an energy carrier, or a substance in which energy can be stored. (Rand and Dell, 2005, 2) This is accomplished in much the same way that the earlier examples of energy storage are accomplished. Energy is used to move a mechanism or a substance from a state of low potential energy to a state of high potential energy and then that energy is stored in that high potential until the substance or mechanism is allowed to fall back to the low potential, releasing the same amount of energy it took to get it to the high potential. This is exactly how the fuel cell hydrogen cycle can be viewed; it is simply moving hydrogen from a low potential to a high potential and then letting it fall back to a low potential when you wish to harness the stored energy.

With fuel cells two of the three potential states for the hydrogen are fixed. The high potential state will always be that of gaseous hydrogen and the final low potential state of the fuel cell hydrogen cycle will always be water. That is, pure hydrogen will always go into the mechanism and water will always come out. But the first low potential
state for the hydrogen can be a wide variety of different substances, such as water, coal, gasoline, or natural gas. (Ogden, 1999, 229; NAS, 2004)

Hydrogen is just an energy carrier because the actual energy source is either in the initial fuel from which the hydrogen was extracted, the source of the energy used to split the hydrogen from the initial fuel, or both. This means that the energy source is either going to be the methane, coal, or other chemical containing hydrogen, or it will be whatever made the electricity to split the hydrogen from those sources or to split the hydrogen from water. The hydrogen itself is simply carrying the energy, storing it for use in the fuel cell.

**5.2- How Fuel Cells Work**

The basic workings of a PEM fuel cell are fairly simple. There are no moving parts within the cell itself and only three main sections. The parts are an anode, a cathode, and a semi-permeable membrane. Molecular hydrogen enters the anode of the fuel cell and within the anode is a catalyst. The catalyst is classically a platinum based material. The catalyst strips the electrons from the hydrogen molecule and reduces the gas to hydrogen ions (protons) and their unattached electrons. The protons are able to pass through the electrolyte into the cathode, but the electrons are not able to. An electrical potential now exists between the anode and the cathode and the only pathway for the electrons to get to the cathode is through an electrical circuit connecting the two. This electrical circuit is whatever electronic device you have connected to the fuel cell. The electrons pass through the device and enter the cathode. Electricity is just electrons
passing through a medium, in the case the circuitry of the device you are powering, so there is now an electrical current. Once within the cathode, they recombine with the protons and with oxygen that is naturally present in the air and form water. (Kotz, 1999, 980) (See Figure 8)

![Figure 7- Fuel Cell Design](image)

Now the beauty of the fuel cell system can be seen. It is possible to have an energy cycle that is completely clean with a fuel that is not only harmless to humans but is beneficial, water. This is known as the solar hydrogen cycle. You take the energy from the sun (or the wind, which is caused by the sun) and use it to split water, separating and storing the hydrogen for the fuel cycle and allowing the oxygen to escape or be used for other purposes. That energy is stored in the split water and is released when the oxygen
and the hydrogen recombine to form water again. The cycle’s beginning and end points are pure water and the in-between states are hydrogen, a non-toxic gas and oxygen, a gas we need to survive.

5.3- Sources of Hydrogen

The cycle is not always so simple in actuality, however, since there is a lot of pressure to produce hydrogen from other sources, usually fossil fuels or bio-fuels, like ethanol. (Ogden, 1999, 239-241) These sources are more complicated molecularly than water and so there are a number of leftovers when the hydrogen is extracted, used for electricity, and finally becomes water. Since the bulk of the molecular makeup of these sources is carbon (by weight) the main byproduct of extracting the hydrogen from these sources is going to be carbon based. While there has been a great deal of interest in learning how to sequester the carbon leftovers from the process of hydrogen extraction there are still a number of uncertainties over its effectiveness.

Additionally, many of these fuels have other impurities, such as sulfur and nitrogen, which would be released by the process. These sources of hydrogen also face the other problems associated with the conventional energy system: fuel security and the fact that we are currently using these fuels in an unsustainable manner so that they will eventually (in some cases soon) run out. If the shift to hydrogen is to be based on these conventional fuels, then the original problems affecting the conventional energy system will still be present.
Of the fossil fuels used to produce hydrogen gas, the process for methane (a.k.a.: \( \text{CH}_4 \), natural gas) is the simplest and most commonly used. It is via this process that the vast majority of hydrogen in the United States is produced, accounting for more than 90% if the total production. (Ogden, 239, 1999) Methane, as mentioned before, consists of four hydrogen atoms bonded to a single carbon atom. The methane is subjected to a process known as steam reformation in order to split the hydrogen away from the carbon.

Steam reformation is a several stage process. In the first stage the methane is heated and steam is introduced. The steam and the methane react according to the following equation:

\[
(\text{CH}_4)_{\text{gas}} + (\text{H}_2\text{O})_{\text{gas}} \rightarrow 3(\text{H}_2)_{\text{gas}} + (\text{CO})_{\text{gas}}
\]

The methane and steam react to form carbon monoxide and hydrogen gas. This gas is then shunted off to another chamber where even more steam is added to the mix and it reacts with the carbon monoxide in the following manner:

\[
(\text{CO})_{\text{gas}} + (\text{H}_2\text{O})_{\text{gas}} \rightarrow (\text{CO}_2)_{\text{gas}} + (\text{H}_2)_{\text{gas}}
\]

In the final stage of the process the hydrogen gas is separated out from the other gasses, purified, and compressed for distribution and use. The waste gasses consist primarily of carbon dioxide, methane, and some small amount of water and carbon monoxide. (Ogden, 1999, 233) (See Figure 9)

Extracting hydrogen from other fossil fuels follows a similar process. The only real differences being an additional first step and that additional waste gasses are emitted. The step that must be added to the process is a gasification of the fuel since oil, coal, and biomass fuels are not naturally gaseous. The resulting ‘syngas’ is then sent through the
same steam reformation process as used with the natural gas. The resulting waste gasses tend to include other trace contaminants, like certain heavy metals, sulfur, and nitrogen. These are the same waste products that result from burning them in a conventional power plant. (Ogden, 1999, 236)

Source: Ogden 1999

Both of these processes operate at high temperatures and are more efficient on large scales. There are efforts to determine methods for sequestering the waste gasses, particularly the carbon dioxide and sequestering them, but that would require additional steps to the process and would increase the overall cost and reduce the efficiency. The main reason that these processes are the most commonly used for hydrogen production is
because they rely on systems that have been set in place already. The bulk of the hydrogen produced up until now has not been for energy purposes, but rather for chemical and industrial uses. The quantities produced have been relatively small compared to the amount that would be needed for a full-scale hydrogen energy system and it has not been subjected to the same problems of security and environmental issues, due to the nature of its use and the small amounts being produced. Steam reformation has been used because the stock fuels were cheaply available and the method was the inexpensive.

Another method that is available is the partial oxidation (POX) of various fossil feedstocks. In POX, the oxygen and the hydrocarbon react at high temperatures and release CO and H₂. This process can occur either with the oxygen that is ambient in the atmosphere or in a highly oxygenated environment. One benefit that they have over steam reformation is that they may be more efficient at small scales and can produce hydrogen quickly in order to better follow electrical demand. (Ogden, 1999)

Another commonly used method of hydrogen production, accounting for a large bulk of the share left by steam reformation, is the electrolysis of water. This process involves the direct splitting of water (H₂O) into its components H₂ and O₂:

\[ 2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2 \]

This is done by placing an electrical potential across a body of water, possibly containing electrolytes (though this is unnecessary), and the electrical potential pulls apart the water molecule forming gaseous hydrogen at the cathode and gaseous oxygen at the anode (Unless the anode being used is composed of a material that oxidizes easily, in which
case it will rapidly do so and instead of gaseous oxygen your anode will turn to a powder and sink to the bottom).

The simplest electrolyzer can be constructed in a glass of water with a 9V battery and some copper wire, but commercial electrolyzers are more complicated and larger in scale. (See Figure 10) There are also technologies being developed that involve permeable membranes, catalysts, and high temperature solid oxide cells. (Ogden, 1999, 237) Regardless of how the electrolyzer actually works, it is essentially the same principle as the fuel cell, only operating in reverse. It is for this reason that electrolysis is often sought as the primary source of hydrogen by many environmentalists.

Figure 9- Electrolysis Basics
Electrolysis can be the cleanest source of hydrogen depending on how the electricity for the process was derived. The electrical source ultimately determines how clean and efficient electrolysis is. The electricity could be coming from zero-emission solar panels or windmills, or it could be coming from a decades-old power plant running on high sulfur coal without scrubbers. This is why it is important not to view hydrogen as an energy source but instead as an energy carrier. If it is viewed as a source than it can easily be used as an example of clean energy or as a zero emissions fuel, when it reality it could be dirtier than clean coal technology or cogeneration plants.

There are also a number of theoretical and experimental technologies for extracting hydrogen from a stock source. These include new membrane technologies for gas separation in the coal gasification process or other improvements to existing technology, but there are also a few completely original methods for extracting hydrogen. One of the technologies that has received the greatest attention has involved using biological processes to produce hydrogen with algae and bacteria. (Ogden, 1999, 240) Another involves the direct photoelectrical splitting of water or other hydrogen-based liquid molecules in wet solar electric cells or by splitting water at very high temperatures. (Khaselev, 1998, 425) These methods are still highly experimental, however, and are not nearly ready for commercialization and introduction into the mass market.

5.4- Hydrogen Storage Techniques

In addition to the many different ways to obtain hydrogen from the molecules in which it is present naturally, there are also a number of different ways to deal with the
hydrogen once it has been produced. When hydrogen is produced in a distributed manner for use in a stationary fuel cell there is little reason to change it from its gaseous state. When it can be kept in gaseous form, it is compressed and stored in a tank similar to that of any gas storage container. But there are circumstances and occasions where the hydrogen might need to be moved and possibly remain mobile, making it necessary to change its form from gaseous to liquid or even a solid.

Pipelines offer an immediate transport solution for gaseous hydrogen, but this option is not always attractive due to the large amount of piping that would be needed along with the costs of installing such a system. Compressing the gas and transporting it via tanker truck might not be able to hold enough hydrogen to make it economically worth the trip. Additionally there have been concerns that enough gaseous hydrogen might not be able to be carried in cars to compete with the current number of miles a car can travel on a tank of gas. (Ogden, 1999, 709) This is one of the concerns that helped to kill the electric car; people have reservations about a car that cannot be taken out of town on longer trips. A final concern is that the gaseous hydrogen might be too difficult to handle at a refueling station and that a liquid or a solid would be preferable for ease of use. (Ogden, 1999, 718)

There are a number of other ways to store hydrogen. One option is to cool the hydrogen gas until it liquefied and then use this liquid hydrogen. Liquid hydrogen would have far more energy for its volume, but it must be very cold to liquefy and the costs of lowering the temperature and maintaining the lower temperature are very high and since it would take energy to do the liquefying the efficiency of the process would drop.
Additionally, handling and transporting liquid hydrogen would involve a number of hazards and risks, the consequences of which could be severe.

Other alternatives for storing the hydrogen in other than a gaseous form are more experimental. Scientists are currently developing metal hydrides and carbon nanostructures that would be capable of absorbing the hydrogen and then releasing it under heat. The hydrides are further along developmentally but they tend to be very heavy, which reduces their usefulness in the transportation industry. The carbon nanostructures are much lighter, but they are still in early experimental and theoretical stages. (Ogden, 1999, 244-246)

The final alternative to gaseous hydrogen storage would be to leave the hydrogen in a molecule that would be easier to handle and then extracting the hydrogen from the molecule at the time you need to use it, this is the process known as onsite reformation. Some methods of doing this involve creating a chemical to contain the hydrogen as a part of its structure but other, more popular, methods involve using the chemicals which we currently extract the hydrogen from such as natural gas or ethanol. If these hydrogen carriers were used to distribute the hydrogen, there would need to be a way to chemically remove the hydrogen on site, or within the car, as you need it. This would add to the bulk of the car and the expense, but it would allow users to utilize the infrastructure that is already available for these fuels in addition to any hydrogen infrastructure that is created. A final problem with onsite reformation is that it might be more difficult to sequester the detrimental emissions that come from the reformation process and it would drastically
reduce the role that solar or wind electrolysis could play in the overall energy system.

(Consonni and Vigano, 2005, 702)

5.5- Fuel Cell Types

One of the final options in the hydrogen fuel cell energy system that can be made would involve the type of fuel cell that is used. This particular choice is more likely to be allowed to vary than the storage technology or the production technology because there is not an overall advantage between the different types of fuel cell and they are likely to be used for varying purposes depending on their strengths. The earliest types of fuel cells were alkaline fuel cells, which were used in the early space program, and phosphoric acid fuel cells. This is the first one that was developed and the one that has been most produced and utilized over the years. Other types of fuel cells are PEM, molten carbonate, and solid oxide fuel cells. Each of these cells operates at different temperatures, some quite hot and others relatively cool. They also have different efficiencies and different sizes and weights. There is also a big difference in the expense between them. The different types of fuel cells are usually separated by two different factors, the temperature at which they operate and by the electrolyte that is used to separate the anode and the cathode. Ultimately the project and purpose will determine the type of fuel cell to be used rather than any one being generally superior to the others.
5.6- The Hydrogen Picture

There are many different pathways along which a hydrogen-based energy system might develop. There are numerous sources of the gas, many storage options, and there are several types of fuel cells capable of consuming hydrogen to provide electricity. These are all options that will have to be considered and duly weighed before any real progress can take place in developing a hydrogen economy. But they are questions of how it will be developed rather than questions of why it should be developed.

It has already been mentioned that hydrogen is not an energy source but just a carrier, and the result of this is that its environmental benefits have to be evaluated by considering the source from which it was derived and the means of its creation. (Dell and Rand, 2001, 10) The same concept applies for its security benefits, as well as its ability to contribute to the formation of environmentally sustainable lifestyles. The reason that hydrogen is important is because it allows us options that we might not otherwise be able to implement. It may allow us to use renewable energy sources in ways that may have been technologically impossible or economically difficult by granting us more control over the energy these methods harness. Hydrogen may be important because it shows a potential solution to the problem of intermittency that might otherwise have proven insurmountable.

The overall picture for the development of a renewable energy infrastructure is daunting. Our society, should it choose to pursue the route of a hydrogen economy has to determine a way to derail our current historical path of energy and start up a new and
different path. The primary problem that is encountered is a chicken or the egg situation. If we wish people to buy fuel cell cars and fuel cells for their homes they will need a source of hydrogen to power them. No one will buy a device that they cannot run and may not be able to run for the foreseeable future. At the same time, an economy of hydrogen production and supply will not start unless there is a market calling for it to be developed. One does not want to start without the other and it is difficult to figure out how to get one to take that first step.
Chapter 6

THE FUTURE OF ENERGY

What good is knowledge without a way to apply it? Either as way to use it to achieve further knowledge, which may itself be useful, or to use it to make the world a better place, to achieve some goal or ambition? How then, might the knowledge in this thesis up until this point be applied? As is stated by Hammerschlag and Mazza (2005) in their paper, “Questioning Hydrogen” the transition to a different energy system will be tremendously costly in terms of money, resources, and time and an effort should be made to ensure that this transition only needs to occur a single time in the near future. Whatever system we choose had better be the one we really want and the one that is optimal for our needs because the level of infrastructure that will be required is not something that can be written off as a loss. A new energy system should be a thing that will suffice for decades and there should be as few regrets about it as possible.

The best thing to do would be to decide what it is that we desire from a new energy system and what problems we have with the conventional one. Then, using what we have discussed up to this point, we can determine what our new energy system might look like and how it might be achieved. Our conventional energy system is antiquated and no longer suitable for a number of reasons.
Firstly the extraction, distribution, and combustion of fossil fuels have incurred serious negative environmental impacts. From the destruction of habitats and environments to the release of greenhouse gasses into the atmosphere, the use of fossil fuels will likely have one of the largest, if not the largest, and longest lasting negative environmental impacts on this planet that man has ever caused. We have literally changed the chemical composition of our skies and seas through the use of these fuels and this will affect every single aspect of life on Earth for decades, if not centuries to come. (The World Commission on Environment and Development, 1987, 174-176)

Secondly, we are quickly using up these resources that we have come to rely on, particularly oil. (Rand and Dell, 2005, 1) There are only limited amounts of these substances and the replacement time for them is measured in thousands of years. As a result what we have now is essentially all that we will ever have at our disposal. Not only are we using them faster than they can replace themselves, but we are accelerating our consumption of them. We are rapidly using up a resource we have no way of returning to the Earth, a resource that is used for many applications other than for fuel, like in the creation of plastics and other synthetic materials. These resources may even have other uses that we do not yet know about that may outweigh their use as a fuel. We need to conserve these resources because they cannot be replaced, and while we can find other energy sources we can never actually get more oil, natural gas, or coal.

Thirdly, prices for many of these goods are rising, just today, March 17th, the price of a barrel of oil hit an all time new high, $56.60 a barrel. (Jad Mouawad, 2005, n.p.) These fuels can be quite expensive and substances like oil do not come in large
quantities from within our own borders. Instead they must be imported, sending more and more of our dollars overseas to a limited number of foreign countries. If a domestic source of energy could be used instead of a foreign one then it would create more local jobs in addition to keeping dollars within the borders. As the resources continue to be depleted, their costs will simply rise higher and the problem will only be exacerbated.

The fourth and final major problem with our conventional energy system is the idea of energy security. As has been shown in the past, relying on a foreign source of oil has its dangers. The 1973 Oil Embargo raised prices rapidly and caused countless problems. Additionally with the current troubles in the middle-east many top political players are considering the dire consequences should the tap be cut off. It may be possible to rely on oil from other sources for a while but ending the black flow from the middle-east would have dire consequences on our economy and the state of this nation’s security.

For these primary reasons many different players, from politicians to environmentalists to academics, have been seeking a viable alternative to our conventional energy system or at least a way in which some of these effects could be mitigated. The most recent of these attempts, and the one that is currently being pushed, is the development of a hydrogen economy. But much of the proposed hydrogen economy is simply hype, a new stage added to an old game with little actual change. (Romm, 2004, 150) The problems listed above are all related to the dependence of the world on fossil fuels, and it is quite possible to have a hydrogen economy that is still a fossil fuel economy at its core.
The only way to fully solve all of the problems above would be to move to an energy economy that is reliant on renewable energy instead of on fossil fuels. Even some renewable energy sources would be questionable, like ethanol and biomass, as they too would still have negative environmental impacts, although less than fossil fuel possibly, that would eventually cause some problems. (MacKenzie, 1992, 31) The only way to achieve an energy economy that solves all of the problems listed above without drastically cutting our total energy consumption before stopping its growth, would be to rely on renewable resources such as solar, wind, and hydro power and to slow and eventually halt our increasing energy demands.

These alternative sources have problems, however. They are expensive, we have difficulty managing the flow of power from them, and they are intermittent, with the exception of hydro, which can only be used in certain locations and has its own environmental complications. These are the reasons we have been using fossil fuels when some of these renewable options have been available, the fossil fuels could more easily accomplish the tasks and at a lower cost. All of these problems are related to the storage of energy. While storing the energy makes it more expensive, it allows these renewable resources to behave in a manner closer to that of fossil fuels. (Schaber et al., 2004, 21)

The production and collection of hydrogen is an energy storage option, the only one that has shown any real merit since the development of batteries other than large-scale options like water pumping and flywheels. This paper was designed to determine which storage option, batteries or hydrogen, would be the most able to solve the problems associated with renewable energies so that they could, in turn, be used to realistically
replace our current energy system and allay our reliance on carbon intensive fuels. As it turned out, both technologies have their strong points in the technical and social worlds. While batteries were overall more efficient than the hydrogen fuel cell cycle, hydrogen was technologically capable of feats that batteries were not. In the social world, batteries are cheaper than hydrogen when only a few are needed, but as soon as the storage capacity needs grow, hydrogen quickly becomes far less expensive. The apparent solution to this quandary appears to be the development of hybrid battery-hydrogen systems that would be able to utilize the technical strong points of both technologies and be less expensive than either one on their own.

Hybrid energy systems have been growing in popularity and in utilization in recent times. The best and most prominent example would be the increase and development of hybrid cars. These vehicles utilize standard gasoline as their primary fuel source but in addition to an internal combustion engine, they also have the ability to run off of a battery. The battery receives its energy by recapturing and utilizing the kinetic energy that is lost in a standard non-hybrid vehicle. The battery can then be used to power the vehicle at certain cycles of its operation, particularly when starting from a stop, which can drastically improve the fuel economy of a vehicle. The popularity of these hybrid vehicles has been particularly astounding, with many people waiting on lists for months before being able to purchase one and with many people paying premiums beyond the normal cost of the vehicle in order to own one.

Hybrid power sources have been used before within the alternative energy field. Examples are renewable energy systems that utilize both solar arrays and windmills
(Byrne et al., 1998, 46), or combining wind generation with small-scale hydropower to try and mitigate the effects of seasonal intermittency in one or the other. (Jaramillo et al., 2004, 1908) Research has shown that it can be economical to buy two systems so that each can be smaller and so that smaller storage is needed to meet the needs of the users when hybrid systems such as these are used. Even a single solar array or wind generator in combination with a battery can be viewed as a hybrid system of storage and generation, essentially the same in principle as the hybrid car. When excess electricity is generated it goes into the battery and when not enough electricity is generated then it can be drawn from the battery, with the hybrid car when excess kinetic energy is present, it can be converted to electrical energy and stored within the battery and when not enough kinetic energy is present it can be drawn out of the battery as electricity and converted into kinetic energy.

Hybrid systems are an effort to compensate for the weaknesses of one type of energy system by combining it with another system that happens to be strong in that area. The weakness in the hybrid cars was that efficiency was low and a significant portion of that efficiency loss was due to the unnecessary loss of kinetic energy. Combined with a battery that energy can now be captured. The weakness of a solar array is its intermittency, both diurnal and seasonal. By combining it with a wind generator a significant portion of the seasonal intermittency can be mitigated and some of the diurnal can as well; the remainder of the weakness in a solar array can be compensated for with the addition battery. The question then is, what can be done to make these types of systems work in the real world and how do we determine the optimal system, be it a
hybrid or stand alone? What needs to be done before these systems will be competitive with the juggernaut of conventional energy? And what issues need to be addressed before this option *should* be pursued, so that it actually solves the problems we found with the conventional energy system rather than simply continue them.
Chapter 7

EFFICIENCY AND LOSS

Efficiency is one of the more highly sought after aspects of many devices today. Everything from cars to microwaves has some method of telling consumers how efficient that item is. It might be in the form of an Energy Star label on it to the miles per gallon being included on the information shown when a person is buying a car, but if one looks for it you can usually find data on a machine’s energy efficiency.

Higher efficiencies in products have a large number of positive effects. These efficiency increases can benefit producers of electricity, government agencies, consumers, and pretty much any party associated with the transfer or use of energy. Because of this, efficiency increase has been avidly pursued, or at least when their benefits outweigh the costs of implementing them. Efficiency must be factored into any situation where energy is being consumed because it will affect how much energy must be produced in order to complete a given task. A high efficiency means that very little energy will be wasted when a function is performed. In some devices efficiencies are rather high and very little energy is lost but in other functions the efficiencies might be so low that several times more energy will have to be produced over what is actually needed since so much of that energy is lost in the process.
Every action has an associated energy cost, and this is the minimum amount of energy that could ever be spent and still have the action occur. Let us look at a scenario in which efficiency comes into play. A book has fallen off of a shelf. In order to put the book back on the shelf 100 joules of energy will have to be used. This is the amount of energy that will always be imparted to the book when it is raised to its original position on the shelf. The machine that is to raise the book back up to the shelf, in this scenario, will be a human being. Now the human being is essentially an engine that can convert the stored energy within it into a variety of other energy forms, such as kinetic energy, which could be used to lift the book. But like any engine, a human being does not operate at 100% efficiency. There are a number of losses due to friction and heat loss so that some of the stored energy a human takes in escapes without being applied to a specific purpose. In this example we will assume that the human body is 80% efficient. So only four fifths of the energy it takes in can be applied to various tasks. So if 100 joules are needed to lift the book back onto the shelf, a human would have to eat 125 joules worth of food. Someone who had a 100% efficient body could lift the book back onto the shelf 5 times for every 4 times that someone with an 80% efficient body could if they were given the same amount of food. The person with an 80% efficiency could still lift the book 5 times but they would require additional food in order to do so, and buying that food would cost them time and money which the more efficient person did not have to spend.

Efficiencies are also multiplicative and they compound on each other in each step of a process. (Rand and Dell, 2005, 10) This can put a multi-stage process at a serious disadvantage in comparison to a single stage process. Returning to the lifting the book
scenario, recall that the human is fueled by food. Well the food is fueled by the sun, and in this stage there are efficiency losses as well. For simplicity, we shall assume that the person subsides on a single food, and that that food is a plant. The plant is able to store energy from the sun within itself at 50% efficiency. So if the plant must have 125 joules of energy stored within it for the person to eat it and be able to make 100 joules of kinetic energy to lift the book onto the shelf, the sun would have to provide 250 joules of energy to the plant! The overall efficiency of the sun to book lifting cycle is equal to 80% * 50% = 40%. Since no action is 100% efficient, each action that as added to the overall process will lower the total efficiency of that process. So if you had a solar powered book lifting robot that could convert solar energy into kinetic energy at a 45% efficiency, that might not seem too impressive when compared to the 80% efficiency of the human being but it actually uses less of the source energy, the sun. Over all the sun would have to only provide 222 joules of energy to the robot, while it would have to provide 250 joules to the plant, which would then proved 125 joules of energy to the human. So even though the robot has a lower efficiency than either stage of the plant/human book lifting process, it ends up having a better overall efficiency.

In the field of electrical production, efficiency plays a very important role. Since efficiency can have such a large impact on the amount of fuel that must be used, this factor greatly affects cost, how polluting an energy system is, how sustainable a system might be or how quickly it might be using up scarce resources. For this thesis, we are looking at renewable energy sources primarily and how that energy might be stored. Both technologies, hydrogen and fuel cells as compared to deep cycle batteries, have efficiency
losses and the extent of these losses will end up affecting several factors. The efficiency of these systems will be a factor in determining how much storage capacity is needed in addition to how much energy production is needed to meet the demands on the system. One of them might end up requiring that a larger renewable capacity be installed to compensate for efficiency losses in the storage process. They may also require additional energy storage if there are different losses in the conversion back from stored energy to usable electricity.

Additional capacity and storage will not only increase the monetary costs of these systems but will also end up using more material resources and land. Since solar and wind power tend to take up an appreciable amount of land already, increasing this amount by even a small percentage could have profound environmental and aesthetic effects. A more nebulous effect of a lower efficiency in utilizing these renewable energies becomes apparent when one considers the limit of the energy that reaches the earth from the sun. While it is unlikely we could ever completely harness this energy for human needs, it is uncertain what effect pulling this energy out of the natural cycle might have. Right now we are using a negligible portion of the world's energy income. Instead we are relying on the world's energy savings, allowing our yearly energy income go towards growing plants, heating the earth, creating the wind and other natural processes. If our civilization begins removing significant portions of this energy from the natural cycles and instead uses it for our purposes the natural world must shrink as the man made world grows. While it is unknown what the effects of humanity using more of the world’s energy income might be, by increasing efficiency we can accomplish the same tasks by
using less source energy and the effects would either be minimized or the efficiency increase would allow for us to have even greater energy demands with the same impact.

In order to evaluate the efficiency of an energy storage medium, such as hydrogen and fuel cells, all of the steps in the process must be taken into account. For this paper the efficiency cycle will consist of the parts of the process after usable electricity leaves the generating unit up until usable energy exits the device. The deep cycle battery storage cycle is simple. Energy goes into the battery and then can be used directly from the battery. Energy can be lost as electricity is converted into chemical potential and when that chemical potential is converted back into electricity. This efficiency is usually grouped into a single efficiency rating for the unit.

To evaluate the hydrogen fuel cell efficiency several more steps need to be examined. Firstly, the efficiency of converting your source of hydrogen into molecular hydrogen, through electrolysis or reformation, must be determined. Other methods are not commonly used or are still in the deep research phases or their development and cannot be considered an immediately viable option for hydrogen production though they may be viewed in some scenarios looking towards the future. The next stage of efficiency that needs to be examined is the storage and distribution of the hydrogen. There are losses in energy when gaseous hydrogen is compressed, liquefied, or changed in any other manner and there are also losses associated with the distribution of the hydrogen if it is not produced on site. The final set of losses that must be examined are the efficiencies of running the hydrogen through the fuel cells themselves.
The final consideration for efficiencies will be whether or not these ratings are likely to change over time. Battery technology is relatively old and is less likely to experience the same level of technological improvement that hydrogen technology may. It could be that hydrogen technology is less efficient in the short term but over the years would develop more fully into a more efficient form. The projected improvements for fuel cell technology must be taken into consideration to produce a full comparison of the efficiency of the two technologies.

7.1- Deep-Cycle Battery Efficiency

Batteries have been around for over a century and have found their way into our every day lives. Lead acid batteries are most commonly used for a source of initial electrical power in large internal combustion engines, which need a significant source of power to start the engines before the combustion process can become self-sustaining. These batteries are designed to provide a large burst of power in a short period of time, not to provide a constant amount of power over a long period of time. As a result a variant of the common car battery is used in situations where the battery is intended to be a source of power for more than a few minutes and is expected to be drained of a significant portion of its energy. These are the deep cycle batteries that are used in electric vehicles and in renewable energy systems that are designed to stored energy for later use rather than being set up in a net metering situation.

One important note in the efficiency of batteries and charging them is that as a battery becomes more fully charged, the efficiency of charging that battery begins to
decrease. This is because it is taking more energy to overcome the opposing voltage within the battery in order to put more electricity within it. It can be viewed as a similar problem as stuffing a suitcase. The first few items go in without a problem, then as the bag starts to fill up you are having to more things around to make room and it is beginning to cause trouble. By the time you have gotten to that last pair of slacks that you need to bring you have to kneel on your bag to squash everything down so you can get the pants in and then zip up the bag. The same principle is occurring with the battery as you increase its charge.

The efficiency is fairly high below 80% charge on the battery but drops significantly as more charge is placed on the battery beyond this level. (Stevens, n.d., 3) So really the efficiency of your battery system depends on how deeply you drain the battery with each cycle, and this in turn depends on how closely your daily electrical usage resembles your peak electrical use for a day during a year. To account for high peak days, you can get a larger battery to accommodate them, but that means that on your average day you will be using a smaller percentage of the battery’s capacity and the battery will be charging at a higher level of charge and thus lower efficiency. The battery efficiency listed on a battery is assuming that the battery is deeply discharged and then fully recharged.

Unfortunately, the average solar energy system is expected to operate most of the time at 80% or higher charge on the batteries with deeper levels of discharge occurring only over extended periods of no sun. Fully charging a battery from 0% to 84% can result in 91% efficiency while charging the battery from 79-84% yields only 55% efficiency.
The loss in efficiency caused by primarily operating in an SOC of 80-100% is allowed because draining batteries below 80% on a regular basis drastically reduces the expected lifespan of a battery and reducing the SOC to even 50% can permanently damage the battery. This level of difference cannot be ignored and must be included as a possible scenario within the overall comparison.

While many batteries are rated at efficiencies of 90% or higher, only a few tests seem to have been done to examine the real life efficiency of these batteries, particularly when applied to use in a renewable energy system. What these tests show is that it is only when the batteries are used in very specific ways and under the optimal conditions (they are often temperature sensitive, as well as dependent on the charging source) that they achieve these optimal charging efficiencies. Ideal charging conditions can occur in day to day use of the deep cycle batteries, but in many situations they do not and charging efficiency drops, which may mean a larger solar or wind array will be needed to fully recharge the batteries in the time before they will be needed again. This will occur when the capacity of the battery is much larger (about ten times larger) than the average daily use so that the battery is consistently drained and recharged in the 90% to 100% state of charge (SOC). This is considered the proper design for battery storage systems in order to obtain a longer lifespan from the batteries.

The range of efficiencies that will be examined will range from 55% (Stevens, 4) and 95% (Hund, 1995, 8) with a middle range of 75% (Wiles, 1997, 1). In that order they will represent the low estimate where the batteries are only slightly discharged with each cycle, the high estimate where the batteries are drained to about well below 80% on most
cycles, and a middle range score indicating a system that is often not being significantly drained but regularly has days where it is.

These efficiencies will be compared to the efficiencies of the hydrogen fuel cell cycle. In this section they will only be viewed in a technical and sustainability context, however later, in the economics section of the paper they will be factored into the energy storage systems cost as the cost of having to increase the size of your wind or solar array to compensate for this loss. Since this is the only stage of the energy storage cycle in deep cycle batteries, this is the only efficiency loss for batteries.

7.2- Hydrogen and Fuel Cell Efficiency

As was mentioned earlier, there are three stages where efficiency losses can occur in the hydrogen fuel cell cycle: production, storage and distribution, and through use in the fuel cell. This thesis is focused on renewable energy systems designed to provide energy to self-sufficient buildings or groups of buildings attempting to produce their own power, so this eliminates many of the possibilities for production and storage and distribution. Additionally the focus of this paper will be on the technologies that are currently available or will be available in the near future, and the technologies that may be available in the future will only be considered when looking at how the passage of time will affect the two technologies.

In the production of hydrogen phase, only two near-future technologies are considered viable and those are electrolysis and reformation. For storage and distribution the primary focus will be on the compression of hydrogen gas. This is because we are
focusing on scenarios where the hydrogen would be produced on site (or at least very nearby). (Schaber, 2004, 22) The efficiencies of all three types of fuel cells (PEM, solid oxide, and molten carbon) will be considered, however, since each of the three could be used in a stationary small-scale power production scenario, though not all would be suitable for transportation. (NAS, 2004) Even with this reduced list of possible technology options, there will still be six different combinations that might come about, each of which will have its own efficiency rating.

A range of efficiencies exists for each technology, because they behave differently under different conditions and at different scales. Additionally, they are broad groupings of technological categories that can contain significant variety in how the devices are actually designed and these differences may yield different efficiencies. The greatest discrepancy in the data reviewed concerns the efficiency of steam reformation. For all of the other categories of technology the efficiencies given in different sources were roughly equal and one was chosen that was representative and inclusive of the majority of the predicted and measured efficiencies. Measures of the steam reformation vary significantly so two different sources are cited.

The efficiency of hydrogen production via electrolysis is relatively high, being rated at between 70 and 85% (chemical potential of hydrogen produced / energy of electricity used in the process). (Ogden, 237, 1999; NAS, 2004) This level of efficiency is close to the level of efficiency stated in the same report for steam reformation of natural gas on a small scale, which was 70-80%. (Ogden, 235, 1999; NAS, 2004) but quite different from the efficiency of 45-70% quoted by the California Energy Commission.
The cause of this discrepancy appears to be whether or not the chemical energy of the natural gas is included as an energy input or not. This is difficult to determine whether or not to include this since the energy value of the natural gas is not a cost of energy to us, but rather a loss of use of that energy from other means. Another question would be to ask if you do take into account the chemical energy of the natural gas, do you take into account the fact that only a portion of that energy would become usable electricity if it were combusted in a combined cycle power plant. Since these questions are unclear both ranges were included.

The fuel cell efficiencies (the electrical energy leaving the fuel cell / chemical energy of hydrogen going into the fuel cell) for all three types are currently fairly close. They seem to have a theoretical efficiency in the mid 80’s percentile, but an applied efficiency of 50-60%. The PEM fuel cell has an efficiency of 50-60% as measured under controlled conditions (Srinivasan, 1999, 324) and could theoretically reach higher but commercially available units usually have efficiencies closer to 30%. Solid oxide fuel cells have a current efficiency of 50-60% but it is believed that the excess heat they generate due to their high operating temperatures could be captured and used for internal heating of buildings which could raise the effective efficiency in some cases to as high as 80-85%. (EERE (a), n.d., n.p.) Molten carbon fuel cells similarly have a measured efficiency of 60% although heat capture systems could be used as they can with solid oxide fuel cells with an overall effective efficiency of 85%. (EERE (a), n.d., n.p.)

Compressing the hydrogen for storage also, as was mentioned above, takes energy. The exact amount of energy it takes depends on how high of a pressure is
attained in the compression, but an average rate of efficiency is 80-90%. (Rand and Dell, 2005, 10) This would be the same across all the combinations of fuel cell type and hydrogen production type. The table below shows the [high-low] efficiencies for the various combinations of technology that could be utilized in a distributed renewable energy home power system.

The combined results of this data can be seen on the next page in both table and chart form. (See Figures 11 and 12) There seems to be little difference between the types of fuel cells used until you add heat capture systems to either the molten carbon or solid oxide fuel cells. This may add a great deal of expense however. The PEM fuel cell can theoretically achieve efficiencies equal or near the other two types and efficiency increases in this would drastically improve its overall efficiency. Electrolysis appears to be only slightly better that reformation in terms of energy efficiency until you take into account the loss of the natural gas as a fuel as an energy input in addition to the energy required to reform it, at which point electrolysis becomes obviously superior in terms of efficiency.
Table 2- Hydrogen Efficiencies

<table>
<thead>
<tr>
<th>Process</th>
<th>PEM</th>
<th>Solid Oxide</th>
<th>Molten Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolysis of Water</td>
<td>28-46%</td>
<td>28-46%</td>
<td>34-46%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45-65%*</td>
<td>48-65%*</td>
</tr>
<tr>
<td>Reformation of Natural Gas</td>
<td>28-43%</td>
<td>28-43%</td>
<td>34-43%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45-61%*</td>
<td>48-61%*</td>
</tr>
<tr>
<td>Reformation of Natural Gas**</td>
<td>18-32%</td>
<td>18-38%</td>
<td>22-38%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>29-54%*</td>
<td>30-54%*</td>
</tr>
</tbody>
</table>

Source: Ogden, 1999

* with good heat capture systems
** includes the loss of energy due to the destruction of usable natural gas

Figure 10- Hydrogen Efficiencies
7.3- Comparing Efficiencies

When the efficiency of electrical storage in batteries is compared to the efficiency of electrical storage in hydrogen for use in a fuel cell, battery technology seems to win hands down. Even when advanced heat collection systems are employed or the theoretical limit of the fuel cells is reached, they still only are competitive with the worst-case scenario for batteries, which is 55% efficiency. (See Figure 13) Because of this data and the theoretical efficiency limit placed on fuel cells by thermodynamics of an efficiency in the 80’s, (Rand and Dell, 2005, 10) it seems unlikely that fuel cells will ever be able to compete with batteries in terms of energy efficiency.

This result makes perfect sense when the laws of thermodynamics are considered. For the hydrogen fuel cell cycle the initial energy must undergo at least three transitions, and at each of these changes there must be an efficiency loss. Every time energy changes form there is a theoretical amount that must be lost, and almost always the amount that is actually lost is going to be greater than the amount that theoretically must be lost due to imperfections in the systems. Even if each stage had a theoretical limit of 90% efficiency, which is very high, the best overall efficiency that could be gained after three conversions is 73%, which would still be lower than the middle ground estimation for battery efficiency. Additionally, achieving the theoretical limit for efficiency is absolutely impossible so the real overall efficiency would be even lower than 73%.
In the realm of energy efficiency, batteries are superior to hydrogen fuel cells, and it seems as though they always will be. This, of course, only holds true under the scenarios whereby a renewable energy system with batteries is capable of putting together a battery bank that is suitable for their load on a consistent basis. This will be
occurring in those situations described earlier where the maximum battery capacity needed is relatively close to the daily average demand on the batteries and they are regularly charged and discharged down to 80% SOC. If this is not possible, and the batteries are in the state of charge range of 90-100% state of charge, it will be far more inefficient to recharge than if it ranged down to at least 80% state of charge. It is only when the battery is usually discharged down below 50% of its capacity that its efficiency will be at or above 90% although this cannot practically occur due to the effects that would have on the lifespan of the battery.

What this means is that if hydrogen and fuel cell technologies continue to improve, and reach 60-70% efficiencies then there may be scenarios where having a hydrogen system instead of a battery system makes more sense in terms of energy efficiency. Hydrogen may end up being more suited for loads which are highly variable from day to day or in situations where they load is usually relatively low but has short periods during the year when demand jumps to a higher level. The efficiency for hydrogen is set in stone once the system is installed but a battery system’s efficiency could vary from day to day, becoming more efficient in the periods where the batteries are relied on more and less efficient when they are not needed as much. If the demand spike can be met by alternative means, such as switching on a generator or drawing power from the grid, then batteries may still be the most efficient means of meeting the renewable energy storage needs for the load, otherwise hydrogen may end up being more versatile in the level of load it can handle from day to day at a consistent efficiency.
7.4- Efficiency Conclusions

While this examination of the energy efficiencies of hydrogen fuel cell and battery technology at first seems to show dominance in the field of batteries, deeper inspection of the situation shows that it is not so cut and dry. Currently, it seems as though batteries will dominate fuel cells in terms of energy efficiency in every situation. But if fuel cells can bring their efficiencies closer to their theoretical limits through improved technology then it seems as though there may be certain energy storage tasks where hydrogen and fuel cells will be a more efficient solution than using classic deep-cycle batteries.

It may be that the efficiencies of fuel cells will improve over time and when they do they may end up being more efficient than batteries in situations where the daily electrical demand is much lower than the electrical capacity of the battery bank needs to be in order to deal with occasional spikes in daily demand. Because this means that on most days the battery bank would be recharging in the 90-100% state of charge, the efficiency will be much lower than it would be at the times when it is recharging the batteries up from closer to 80% state of charge.

In order to determine which system would be more efficient for your particular needs you would have to compare your average daily demand on the battery bank to the size of the battery bank that would be needed to deal with your peak days. It seems likely that in most cases the battery bank will still be the better choice in terms of energy efficiency, but there could be scenarios where the hydrogen and fuel cell system would give better results.
Chapter 8

TECHNOLOGICAL ISSUES FOR ENERGY STORAGE

One important question that needs to be answered is whether or not each storage technology is capable of serving the needs of a particular load and which one might be better suited to do so. In order to do this we must examine what the technical limitations of each technology are in the field of providing electrical power to a load. An example of this in the field of transportation, would be refueling time. Regardless of the other differences in the field of transportation between hydrogen and batteries, when each car runs out of stored energy there is a major difference in the time it takes them to be ready to drive again. A battery powered car must recharge for hours while a hydrogen powered car simply would need to find a hydrogen station and refill, which would take a matter of minutes. This is not to say that one is essentially better than the other overall, simply that there are some things that hydrogen can do that batteries might not be able to and it works the opposite way as well.

When it comes to distributed electrical generation, the differences become less apparent. Neither systems is intended to run out of hydrogen or electrical charge, as they should be designed to recharge with hydrogen or electrical power during the periods of excess renewable production. Because of this the refueling problem illustrated above certainly doesn’t apply. There are also not concerns about weight or strict control of size
of the systems because they do not need to be transportable or fit within the shell of a car. If the discussion were limited to the field of distributed electrical generation, many of the envisioned technical benefits of hydrogen over batteries would not be present.

This does not mean, however, that there are no other pertinent technical differences between the two technologies. There are still questions of energy density since these storage mechanisms must be able to fit on the premises to which they are providing power. There is also the possibility that sometimes your system might fail, either because you didn’t produce enough power from your renewable energy system or your storage fails, and it must be questioned which of these technologies would be better capable of dealing with such situations, which is most flexible. The final point that must be examined is in the capability of the two media in dealing with seasonal intermittency in addition to day-to-day intermittency. That is, there is a question as to which energy storage technology might be better suited for situations where energy produced during the summer must be stored and used in the winter. Which technology is better at storing the energy over long periods of time?

These questions must be examined as they may show certain aspects of power generation that hydrogen or batteries are better at than the other. While it seems unlikely that one storage media will be able to do much that the other absolutely cannot, it is quite possible that one will simply be superior in certain aspects of its technical performance under certain circumstances. We must also try and envision how this distributed energy system will fit in with the rest of the energy system of our society, like transportation and industrial energy use. While either storage system could compensate for such a handicap,
it may eventually affect the overall cost and environmental impact that these systems have.

8.1- Energy Density

‘Energy density’ refers to how much potential energy can fit within a certain volume. This quality of an energy storage system is of particular value in the alternative transportation field because the tradeoffs between vehicular range and the size of the energy storage systems greatly affect vehicle use and consumer appeal. One of the barriers that have stifled the market for electric cars is the limited range in comparison to conventional internal combustion engines. While they are perfectly fine for driving to and from work or around town, the difficulty and time required to recharge the vehicles makes them ill-suited for long trips or speedy refueling. Even if 95% of the days a person drives would be unaffected by this limitation, many consumers may not want a car that is incapable of doing what their current car can accomplish. In this case the energy density of batteries is too low to make them acceptable for long trips. Simply adding battery capacity to extend vehicular range is offset by reduced space within the car and the weight and cost of the batteries.

As stated, this quality is not quite so important when the energy storage system is not being used in the field of transportation, but rather is being applied to a stationary power production application. But the size of these systems may still be a factor in the adoption of one system over the other. In the section regarding energy storage techniques involving the mechanical storage of energy I mentioned that energy could be stored by
having a giant weight in your basement that would be raised and lowered as it stored and released energy. The problem with such a system is that it might take up a large portion of someone’s basement or yard. The same issue applies to both hydrogen and battery storage systems. While they will be smaller than the weight system they may both still take up a significant amount of space and if one can store the same amount of energy in a smaller space, such a technological advantage might make that technology seem much more attractive to consumers.

For the battery scenario, the question of energy density is fairly simple. The only component in the storage system is the battery and they have fairly well defined energy densities. Manufacturers list the energy density of their products usually in Amp-hours, which is not actually a measure of work or energy, but rather a measure of the storage capacity. Amp-hours may be converted to Watt-hours (W-hr) by multiplying the Amp-Hours by the voltage at which the Amps-hours are operating. For a battery of the sort we are interested in, the initial voltage is 12 volts and fully discharged is considered to be 10.5 volts. The voltage potential of these batteries on average is then 11.25V. So to calculate the W-hr rating of these batteries their Amp-Hour rating was simply multiplied by 11.25V. This gives us the energy part of the energy density equation but to calculate the energy density the volume of the batteries is needed as well. The manufacturers also provide the dimensions of the batteries and with a few conversions the volume of the batteries in meters cubed (M$^3$) can be easily calculated. The energy density can then be calculated by dividing the W-hr by the M$^3$. Additionally, all values have been converted into mega-joules per meter cubed (MJ/m$^3$).
Sorensen calculates that a lead acid battery is capable of holding 100-900 MJ/m$^3$ per battery, which is a rather large range. (Sorensen, 1984, 6) A narrower estimate can be obtained by looking at the deep-cycle lead acid batteries produced by US Battery, Inc., specifically at the line they marketed for renewable energy purposes. The table below summarizes the data used.

Table 3- Data Used to Calculate Energy Density of Batteries

<table>
<thead>
<tr>
<th>Model #</th>
<th>Amp-Hr</th>
<th>Length (in)</th>
<th>Width (in)</th>
<th>Height (in)</th>
<th>m$^3$</th>
<th>Amp-Hr/m$^3$</th>
<th>kW-hr/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>US-250</td>
<td>250</td>
<td>11.5</td>
<td>7</td>
<td>11.5</td>
<td>0.015</td>
<td>16447</td>
<td>185</td>
</tr>
<tr>
<td>US-250HC</td>
<td>275</td>
<td>11.5</td>
<td>7</td>
<td>11.5</td>
<td>0.015</td>
<td>18092</td>
<td>204</td>
</tr>
<tr>
<td>US-305</td>
<td>305</td>
<td>12</td>
<td>7</td>
<td>14.5</td>
<td>0.02</td>
<td>15250</td>
<td>172</td>
</tr>
<tr>
<td>US-305HC</td>
<td>335</td>
<td>12</td>
<td>7</td>
<td>14.5</td>
<td>0.02</td>
<td>16750</td>
<td>188</td>
</tr>
<tr>
<td>L-16</td>
<td>375</td>
<td>12</td>
<td>7</td>
<td>16.5</td>
<td>0.023</td>
<td>16520</td>
<td>186</td>
</tr>
<tr>
<td>L-16HC</td>
<td>415</td>
<td>12</td>
<td>7</td>
<td>16.5</td>
<td>0.023</td>
<td>18282</td>
<td>206</td>
</tr>
</tbody>
</table>

Average = 190
MJ/m$^3$ = 683

Source: The Alternative Energy Store

This result fits right in with the estimate provided by Sorensen and will be used as the best guess value for the energy density of batteries, with the high and low values providing the boundary energy densities.

Sorensen also provides data regarding the energy density of hydrogen as a fuel. He states that hydrogen gas has an energy density of 10 MJ/m$^3$, liquid hydrogen has an energy density of 8,700 MJ/m$^3$, and hydrogen absorbed into metal hydrides have energy
densities of 5,000-15,000 MJ/m$^3$. (Sorensen, 1984, 6) At first this seems to be an abysmal set back for hydrogen, since we are primarily interested in using compressed hydrogen for purposes of efficiency in this paper. But what needs to be realized is that this energy density applies to uncompressed hydrogen, and the energy density will increase dramatically as the gas is compressed. The energy densities for the liquefied and the absorbed hydrogen seem to indicate that the energy density of hydrogen can reach high levels if stored properly.

In order to determine the energy density of compressed hydrogen, data from the California Energy Commission was used. (California Energy Commision, n.d., n.p.) They had conducted a study based on transportation, and as energy density is such an important quality for a fuel in the field of transportation they provided data that enables the energy density of hydrogen to be calculated. In their report they gave the energy of the compressed hydrogen in MJ and gave a range of volumes that this hydrogen would take up in liters. A range was given because there is not a set level that hydrogen must be compressed to and the further the gas is compressed the higher the energy density. The energy of the hydrogen used was 664 MJ and it was compressed to a volume of 227-409 liters. This volume is easily converted to m$^3$ and then the two are combined to yield the energy density. These values yield an energy density of 1623-2925 MJ/m$^3$ for compressed hydrogen gas.

At face value this means that the same amount of energy in the form of lead acid batteries would take up roughly 3 to 5 times the space that compressed hydrogen gas would. But while batteries are all that are needed to store and extract the energy in that
scenario, hydrogen requires not only the storage tank for the compressed gas but also an electrolyzer or a reformer to make the hydrogen, a compressor to reduce the volume of the gas, and the fuel cell itself to create electricity from the stored hydrogen gas, all of which would take up space.

In order to see how much impact the addition of the other components of the hydrogen fuel cell system would have on the effective energy density of the hydrogen storage system, we need to first estimate roughly how large the actual storage tank would need to be. If it is much larger than the size of the other components then their size can be ignored, but it is on the same scale as them then their size must be factored into the effect energy density of the hydrogen storage system.

In order to accomplish this an estimate of the daily energy use of a household is needed, so an estimate of how large the storage system would need to be may be obtained. According to the Energy Information Administration there are 107 million households in the US and 1.14 trillion kWh of electricity were used. (EIA, n.d., n.p.) This equates to 29.2 kWh being used each day in each household. This is an average based on the aggregate of all the households in the US over the entire year, and perhaps more importantly it only includes the energy used in the form of electricity and doesn’t include the energy uses from heating oil or natural gas. 29 kWh a day equates to 104 MJ of energy used in an average household on an average day, just from wall current. If the household’s entire energy demand were to be met by the renewable energy system, then this figure would need to be increased.
Bases on the assumption that the user is being conservative and gets enough storage capacity to last an entire week, meeting the entire daily electrical demand, without additional input from the renewable energy system. This means that the storage system would be 728 MJ in capacity. Under this scenario, the battery bank would be roughly a cubic meter (1.07) in size and the hydrogen storage tank would need to be around 0.25-0.45 cubic meters in size. This is a significant amount of space, and it will grow larger if the renewable energy system begins to take on other roles such as heating, cooking, and hot water that were not included in this example if they were not electric in nature to begin with.

What remains to be seen, however, is just how large the electrolyzer, compressor, and fuel cell would be and whether or not they would take up this extra space. Additionally, the amount of space taken up assumes that the total mass can be lumped and stacked together. This is true for a hydrogen storage tank, but it may not be true for a bank of batteries, which might need some space between them so that they can be accessed, allowed to vent, and connected. Also, the larger the system, the better the hydrogen and fuel cell scenario will look because the storage capacity will grow in both cases but the electrolyzer, compressor, and the fuel cell will not. So the more storage a system needs, the better the hydrogen will look because of its higher energy density, but at the same time, in terms of space smaller renewable energy systems that only need to store small amounts of power will favor the batteries because they would not need all that extra equipment.
A fuel cell to supply the power output to meet the average domestic electricity demand is of quite modest size. A 1000 watt PEM fuel cell takes up about 0.13 cubic meters. (Ballard Power Systems, n.d., n.p.) Since the average house described above uses 29 kWh a day and the maximum power that this fuel cell could put out assuming the demand was spread out equally across the entire 24 hour day is 24 kWh, it can be assumed that a household would need at least two fuel cells of this size, possibly three depending on size of the house. This brings the space used by fuel cells up to around 0.26-0.39 cubic meters. At this point the fuel cells alone will take up approximately the same size as the storage tanks that would be needed to supply the fuel cell.

![Figure 12- Graph of Space vs. Storage Capacity for Hydrogen and Batteries](image)

Figure 12- Graph of Space vs. Storage Capacity for Hydrogen and Batteries
An electrolyzer would not be too large, only about 0.029 cubic meters for a single unit. (Udomi, n.d., n.p.) Even if several were required to make enough hydrogen to satisfy demand they would not take up more that 0.1 cubic meters. Additionally it is possible that the fuel cell itself could be operated in reverse, performing double duty, converting water to hydrogen when excess electricity is being generated by the renewable energy array and then converting that hydrogen back into electricity when it is needed. In this scenario no additional space would be needed for an electrolyzer. Similarly hydrogen compressors come in sizes that are relatively small. One offered by Hera Hydrogen is only 0.008 cubic meters in size (Hera Hydrogen, n.d., n.p.), so even if one ten times larger than that were needed it would take up at most 0.1 cubic meters of space.

The net result for the effect of the additional components on the overall size of the hydrogen storage system is that, at most, our average household would require 1.04 cubic meters of space, assuming the worst-case scenario for each component. This is approximately the same amount of space that a battery storage unit of similar capacity would take up minimally. If the storage systems needed to be larger, the gap in size between battery and hydrogen storage would continue to grow in hydrogen’s favor. (See Figure 14)

Ultimately, it seems unlikely that the energy density and size of the system will play an important role in deciding between battery-based storage and hydrogen-based storage. While hydrogen does have the advantage in situations where large amounts of energy will need to be stored, the advantage is relatively small in actual importance.
Where this advantage might become important are in areas that are highly seasonally intermittent. In areas where solar power is the better option over wind, but there is a large difference between the amount of solar energy available during the winter as compared to the summer there are two options. The first option would be to build a system that was large enough so that even when there was not much sunlight it could provide enough day to day or week to week electricity, but then during the summer you have a massive over production and it would be inefficient for economic and resource reasons. The other option would be to store large amounts of energy from the summer for use during the winter. (Chapparro et al., 2005, 1) In this scenario the household would not be producing enough electricity on a day-to-day basis in the winter, but the difference could be made up by drawing from the store of saved energy from the summer. Santarelli and Macagno in the Italian Alps demonstrated this sort of system with a hydrogen based storage system. (Santarelli and Macagno, 2004, 1177)

The point of this argument is that in a scenario like the one described above, large amounts of storage might be needed, not a few day’s worth, but perhaps as much as a full months worth of stored energy to make it through the season where you are producing insufficient energy to meet demand rather than an excess or even an equal amount as compared to what you are using. Ultimately there are enough variables that in some systems hydrogen will be preferable and others where it will not matter so much. Small systems that try to balance themselves out on a day-to-day basis will lean slightly towards battery storage, whereas larger systems that need to balance deficits and excess from one season to the next may favor hydrogen.
8.2- Comparative Technical Advantages

The question arises, are there any tasks which either hydrogen or batteries are capable of that the other is not? It has been already shown that batteries are likely to be more efficient in the overall scheme of things due to their singular nature in electrical conversion, and it has also just been seen how in terms of size that batteries may take up more room in most situations, but the size would likely be no more than twice that of a hydrogen storage system (1 cubic meter larger) for systems that are on a household scale, and this is not a size which is prohibitive.

There are two issues where hydrogen does clearly dominate in its technical capabilities. The first is in the field of transportation and the other is hydrogen’s ability to store massive amounts of energy over long periods of time. Both of these issues are only advantages however of one does not think creatively for the battery technology.

As was stated earlier, hydrogen has the advantage over batteries of quick refueling times. For transportation this is a big advantage when great distances (hundreds of miles) need to be covered but it has relatively little impact on the average day-to-day travel. If hydrogen were being used as a storage medium on a local basis already, the availability and diffusion of hydrogen-based technology would positively impact the hydrogen transportation industry and the other way around as well. The two could easily work off of and balance each other in a symbiotic relationship. If hydrogen is the dominant option for clean transportation then it makes some technological sense to have compatible and similar technologies in other places as well.
The advantages of hydrogen in terms of transportation, however, are not so grand as they might seem. As I have already mentioned, the ability to quickly refuel in the middle of long trips will likely only be needed for the average driver in less than 5% of trips, likely less than 1% of all trips made. So to begin with that advantage isn’t really an advantage most of the time. Battery powered vehicles also do not need to rely on their batteries alone. Hybrid electric vehicles could be manufactured that would run off of the renewably charged battery for the majority of trips and on the few trips that required great distances to be traveled a fuel powered generator could be run that could provide power and easily be refueled at stations. They could run off of ethanol, gasoline, hydrogen, or any other fuel giving the hybrid vehicle long-range capability. Even if the fuel used emits carbon dioxide or other greenhouse gasses, since it would be used so infrequently the overall emissions will still have dropped dramatically, potentially well below the environment’s ability to absorb, especially since these gasses would only need to be produced in the transportation industry and not in the electrical or heating industries, assuming an overall shift to renewable energies.

That leaves hydrogen’s ability to deal with seasonal intermittency. Hydrogen has the advantage over batteries in that it is relatively cheap and easy to add storage capacity to a hydrogen system. In areas where renewable energy systems would be producing insufficient electricity for months at a time this capability would be one of the few ways in which a yearly balance of energy produced versus energy used could be maintained. However, until this point, the scope of my study has been relatively narrow, primarily
considering a situation where a house or building must produce all of its own electricity and have the ability to store that energy for times when it is needed.

The problem of seasonal intermittency is quite important, but primarily in standalone energy systems that rely on one renewable technology. In more realistic scenarios buildings and households would be able to have dual renewable energy systems, like solar panels and wind generators, the combination of which would mitigate the effects of seasonal intermittency in one or the other. Additionally, in most situations a household would be able to tie into the electrical grid and balance their electrical production and demand with not only a central producer of energy, but also with other households. If there is still a problem of seasonal intermittency then a central storage system of the excess electricity and distribution of that energy through the grid when it is needed would likely be more efficient in terms of energy and economics than attempting to store massive amounts of energy on the premises of your household would be. A central storage system could make use of some rather efficient large-scale storage technologies like superconducting electromagnetics, water pumping, or even a large-scale central hydrogen production system. (Schaber, 2004, 22)

The end effect is that in terms of technological capability hydrogen seems to only have the ability to do things that could not be accomplished with batteries or central storage when the household is cut off from outside inputs and there is a need for large amounts of storage capacity in order to deal with seasonal intermittency or occasional spikes of energy demand that far exceed the average daily use of electricity.
8.3- Technological Conclusions

Hydrogen storage technology has long been promoted for its abilities to accomplish our current energy demands in a renewable way, even those energy demands that previous technologies were unable to. It has been touted as a fuel for cars that will be ‘green’ without any of the loss of utility that was perceived with battery powered electric vehicles. It has been seen as a solution to the problem of intermittency and in being such a solution it has been seen as opening the pathway to developing a renewable energy system that could supplant our current energy system.

But technologically, hydrogen seems to have few advantages over conventional energy storage systems, like deep-cycle lead-acid batteries. In terms of efficiency, it fails to surpass batteries due to the many stages hydrogen must pass through from the initial input of electricity to the final output. Batteries may take up some more space due to their lower energy density, but even if the needs of the average household were tripled or quadrupled, the volume that a battery bank would take up would only be a few cubic meters. The final perceived technological advantage is its ability to deal with intermittency. In terms of day-to-day (diurnal) intermittency, batteries are just as capable of handling the problem as hydrogen. For the seasonal intermittency, other options could be available such as hybrid renewable energy systems that would be out of phase with each other in terms of their intermittency cycles or by tying into a central storage system or neighboring regions that might be able to access different renewable energies that are out of phase with the renewable energies that are available to your household or region.

(Schaber, 2004, 22)
While this thesis has not yet looked at the economics or environmental impacts of these systems, it seems as though from a purely technological viewpoint, in terms of the two storages techniques’ abilities to work within a renewable energy structure, hydrogen has not shown the ability to accomplish anything that could not be accomplished through other technology options, especially lead-acid deep-cycle batteries. Additionally these alternate technologies seem to be able to accomplish these storage tasks more efficiently than the hydrogen storage is capable of accomplishing them.

So purely from a technological view, ignoring what may or may not be uncovered in the later sections of this paper regarding the economics and environmental impacts of the two storage technologies, there does not seem to be any reason to move to hydrogen storage of energy over our conventional methods. The exceptions to this may be in situations where a building or household is cut off from outside input of energy other than their own renewable energy systems, in situations where there is a large amount of seasonal intermittency that cannot be mitigated through a connection to a regional grid or mixing renewable energy types, and for long distance transportation or other vehicles that need to run for extended periods of time. In all other situations, hydrogen and batteries are essentially the same in their capability to provide energy storage for our needs and battery technology is likely to remain more efficient than electrical to hydrogen to electrical conversion due to the theoretical limits imposed on the efficiencies of the various steps in the hydrogen process. From an entirely technological viewpoint, the best that hydrogen will likely be able to accomplish, assuming advances in technology, will be competitiveness with batteries, not the dominance that is often envisioned.
Chapter 9

ECONOMICS AND EXPENSE

The physical characteristics of the two technologies seem to indicate that battery technology would be superior in many ways for the storage of energy than would the hydrogen fuel cell technology. This may seem incongruous given the tremendous amount of attention that the developing hydrogen economy has been receiving and the relative lack of excitement regarding renewable energy options in general, let alone the use of batteries for storing that energy. One would think that with batteries being at the very least equal in technological capability to hydrogen that this other technological option would be given some attention in the media and government press releases.

Up until this point in the thesis, the discussion has been dominated by the physical aspects of the two energy storage systems: batteries and hydrogen. But what may play an even larger role in determining the future of our energy system may be the social rules and how the different energy options interact with them. The two primary factors in the social world that will factor into the development of a new system are security and economics. For decades the energy industry has been utterly dominated by fossil fuel sources and it still is. There has consistently been a tremendous resistance to moving away from fossil fuels despite the growing concern over their future availability and the environmental impacts they incur. One reason for this is because the fossil fuels are less
expensive than most alternative energy sources. A coal-fired power plant can produce a kilowatt-hour for a few cents and the fuel is available domestically making it strong in both fields of economics and security.

When it comes to energy storage, batteries in most situations are physically superior to hydrogen. This stems from their higher efficiencies in day-to-day use, leaving hydrogen the niche applications of long-range transport and seasonal energy storage. But the social world has been largely untouched thus far, and it is in this arena where decisions are more likely to be made, not in the physical one. Even now the hydrogen economy is crawling forward while battery energy storage largely died out as a popular topic over a decade ago. To understand why this is occurring we must examine the social aspects of energy storage, the economics of hydrogen and batteries.

9.1- The Expense of Transition

While the social world and its laws are a construct of our collective minds, that in no way means that they can be dismissed as unimportant. Despite being non-physical and intangible they are an intrinsic part of the world we live in and play incredibly large roles in determining the behaviors of the people on this planet. In order to enact a change, the new pathway must fit within the social rules otherwise people simply will not adopt it, even if there are obvious flaws with their current way of life. Expense and money are a construct of our social world. Money represents work done and the ability to survive in the western world and it also represents resource. As such a medium it is given power by
the people who use it and in an effort to change the energy system it should be given its due.

As it stands now, a shift in the energy system will require a great deal of capital. In fact, it will require so much capital, resources, and effort that it is an endeavor that should only be undertaken a single time. It is sufficiently expensive that the system we choose to move to had better be the correct one because it is not an effort that can be repeated each year or even every decade. The expense of transitioning to a hydrogen economy has been estimated to cost between $200 and $500 billion (Hammerschlag and Mazza, 2005, 2039) and regardless of exactly how much it costs, it should only be done a single time if it can be helped.

9.2- The Current System

As was mentioned earlier in the thesis, the expense of our current energy system is less than the other energy alternatives we have at our disposal. While this may be due to market distortions and the failure to include the social and environmental costs of the system, it is the way our energy system is currently set up. The following discussion is not supposed to show how a new renewable energy system could be less expensive than the current one, through one energy storage technique or another, because by the very nature of the efficiencies of energy storage and the laws of thermodynamics they can only increase the expense of renewable energy. Instead, this section is designed to illustrate the most cost effective means of energy storage that is available between the two
technologies that appear to be technologically dominant for the near future, hydrogen and batteries.

**9.3- Expense**

While batteries appear to be technologically dominant over hydrogen for every day use, in terms of energy storage, hydrogen actually appears to be less expensive for meeting a household’s energy demand. This appears to be primarily due to the fact that while hydrogen has a number of expensive components, such as an electrolyzer, a compressor, and the fuel cell itself, the storage for the hydrogen gas is relatively cheap and increasing the size of the storage tank to allow for a higher storage capacity is not terribly expensive. Batteries on the other hand do not require additional components but each unit of storage costs as much as the previous, and the combined cost of the storage quickly surpasses the cost of the various components required for hydrogen based storage. While battery cost is almost entirely dependent on the size of the system, hydrogen storage is not. Additionally, the majority of the parts in a hydrogen system last between ten and twenty years, or even longer. Batteries, however, wear out after a certain number of discharge charge cycles and then must be replaced; most deep-cycle batteries are rated for only ten years of use by their manufacturers, and they realistically last for a shorter period of time than that. (Vosen et al., 1999, 1144)

Much of the reason for hydrogen to be less expensive than batteries lies in the fact that hydrogen is capable of storing large amounts of energy for long periods of time with only a slight increase in cost. The cost of a battery system rapidly increases as the storage
capacity is expanded to try and carry energy from one season over into the next. For this reason, hydrogen is less expensive for long-term energy storage than batteries. (Shakya et al., 2005, 10) Several studies have been done showing the disparity in the costs between these two media and what follows is a description of some of their findings.

The costs of hydrogen, as mentioned earlier, are heavily weighted towards the equipment required to process the stored hydrogen rather than the storage itself. Isherwood et al. state that a fuel cell costs $1,500/kW, although others have calculated higher costs and these will be examined later, and an electrolyzer costs $1,000/kW. The cost of compressing and storing the hydrogen, however, amounts to only $10/kWh of storage. Using these figures we can arrive at a rough estimate of the cost for a system to service our “average house” with average electrical use from before. (Isherwood et al., 2000, 1011)

Before modifying the “average house’s” storage needs to account for seasonal intermittency, it was estimated that roughly a weeks worth of backup power would be a good amount of storage space. (Shakla et al., 2005, 13) This amounts to 203 kWhs of storage. Combined with a 5 kW fuel cell (large enough to meet peak demand) and a 3 kW electrolyzer, the total cost for the hydrogen energy system would be $2,030 for storage space and compression, $3,000 for an electrolyzer, and $7,500 for the fuel cell. The total hydrogen gas energy system would cost $12,530.

Vosen et al. place the costs of the various components higher than Isherwood estimated. They place a fuel cell cost at $2,500/kW, the electrolyzer at $1,900/kW, and the storage and compression components at $30/kWh. Using these prices our household
system would cost $12,500 for the fuel cell, $5,700 for the electrolyzer, and $6,090 for the required storage. This would yield a total system cost of $24,290, almost twice as expensive as the first estimate by Isherwood et al. For the cost of batteries, Vosen et al. state that the cost of storage would be $200/kWh. This would yield a total system cost of $40,600 for the storage. (Vosen et al., 1999, 1144) One important point to make is that the two technologies being compared are not at the same level of maturity. Batteries have been around and in common use for far longer than fuel cells, which are just emerging into the common market and have not had as much time to develop. The true cost of fuel cells once they have reached a higher level of maturity has yet to be determined.

As was mentioned before, the hydrogen and fuel cell systems have a longer expected lifespan than the battery systems. Using Isherwood et al.’s data regarding the lifespan of each component, we see that they estimate each piece of the system has a lifetime of 20 years. This means that the simple yearly cost of storage for the average house using their figures would be only $618. Vosen et al.’s data indicates that the hydrogen storage and compression system would have a lifetime of 10 years, and the fuel cell and electrolyzer both have lifetimes of 5 years. This would yield a simple yearly cost of $2,500 for the fuel cell, $1,140 for the electrolyzer, and $609 for the storage and compression, for a total simple yearly cost of $4,249. Their data states that the lifespan of a battery used in this manner is only 4 years. So for the simple yearly cost of the battery system it would be $10,150/annum. This last number may be slightly lower as the entire battery system which accounts for the $200/kW price may not need to be replaced on this regular basis.
This data also only covers the “average house” scenario and with the specter of seasonal intermittency as a threat to batteries’ technological ability to handle a household’s electrical load, how will it affect the economics of the energy systems? Let’s say that in order to deal with seasonal intermittency, the actually storage capacity will need to be twice the size it is in the average house scenario, though it might well be more than that depending on the situation. So if the storage capacity needs to be doubled, then the cost of the battery system will be doubled to $20,300/year, since capacity and cost have a 100% correlation in the battery scenario. (See Figure 16)

![Figure 13- Cost Vs. Storage Capacity](image-url)
With a doubling of the hydrogen storage capacity, however, the cost will not double because capacity and cost are not 100% correlated. Instead only the cost of the storage component will double, increasing from $609/year to $1,218/year. So if the capacity were doubled, the cost of the hydrogen storage system would increase from $4,249/year to $4,858/year using Vosen et al.’s data and from $618/year to $728/year using Isherwood’s data. So as can be seen in the graph below, the cost of a battery system is extremely sensitive to the capacity of that system and any increases cause the price to rise dramatically, while the hydrogen storage systems are only mildly effected by capacity increases.

Looking at the graph, there is an obvious point of interest and that is where the cost of the batteries equals the cost of the hydrogen storage system according to Vosen et al.’s data. Using the function that was utilized to create the graph above, it can be calculated that the capacity required for the battery system to equal the cost of the hydrogen system is 77.14 kWhs, or 2.66 day’s worth of energy storage. For the cost of batteries to equal the cost of hydrogen using Isherwood’s data, the storage capacity would have to be well under a day’s worth of back up energy.

While there are some locations in the United States where having only two and half days of back up power might be suitable, it would certainly not be a viable option for an area that had any level of seasonal intermittency at all. Recall also that the amount of energy needed by our “average house” only accounts for the current average electrical consumption and does not include any energy that comes from natural gas or oil for cooking, heating, and other purposes. Also as this is just the average household’s
demand, the numbers could grow larger quite quickly. On the other side of the coin, this figure is based off of an average *American* household. The demands made by a household in a developing nation would understandably be quite a bit less and would likely favor the battery systems for cost, unless the system was servicing an entire community or group of houses.

So what we have here is a situation where one technology is favorable in the physical world and another is favorable in the social world. Batteries are more efficient and would, in the long term, be the best solution for effectively using the planet's resources. But the expenses could be prohibitive. It is unlikely that could afford the $10,000 a year to support a full battery bank and that is not even a cost that could be shared by a group, as the number of people increasing would simply increase the storage needed. Even if this number is too high, even if it were cut in half the price would still be unacceptable. Hydrogen has yet another advantage in this realm in that it is a relatively new technology that will likely continue to drop in price as it is further researched and an economy of scale is built up. Yes, batteries are more efficient, but even if extra generation capacity needs to be added in the form of wind or solar power to make up for the lower efficiency, hydrogen will still be cheaper.

**9.4- Scenarios**

Several studies have been conducted that have taken real world situations, either a household or a community and set up stand alone renewable energy systems in order to see if the technology can actually accomplish the task and to see what the economics of
the various scenarios actually turn out to be. In this section we will briefly look at a couple of these studies and how their findings compare to the findings that were achieved above. Some of these studies look just at the situation with batteries, others with just hydrogen, and some test both and compare them, what follows will focus on the two studies that were used as sources of data for the economic modeling in this paper.

The first study to be examined is Isherwood et al.’s (2000). This study examined a hypothetical Alaskan community, created from data obtained from the University of Alaska and real Alaskan villages, and how adding renewable energy resources would be able to cut down on their energy costs. The community in question is remote and pays heavy fees for electrical service and relies heavily on diesel generators, the fuel for which has to be imported at high expense. Due to the nature of the environment, both wind and solar are highly intermittent. These factors combine to create the perfect scenario for hydrogen and fuel cell storage for renewable resources. Battery storage was not considered as an option for the community.

The study concluded that by adding the renewable energy option to the existing energy scenario, economic savings would occur and that if hydrogen storage were taking place the savings would increase even further. These energy savings are primarily due to the extremely high costs of conventional energy and could not be expected in your average community. Additionally, the maintenance required of the systems was lessened due to the fact that, unlike diesel generators, fuel cells have no moving parts. Further savings were accrued by the fact that fuel cells are essentially noiseless and thus could be kept close to buildings, allowing for a greater recovery of waste heat. Even though the
efficiencies of the system were only around 30% for the production of electricity, waste heat recovery increased this. (Isherwood, et al., 2000, 1007)

Overall, this scenario was the perfect area for hydrogen storage technology. Conventional energy was relatively expensive and the area was highly seasonally intermittent. This required large amounts of storage, which hydrogen can provide relatively cheaply. While it is rare that in our current energy system a hydrogen storage system will be able to provide energy cost savings, it is a situation like this, a remote, standalone community that is highly seasonally intermittent where savings might be possible. The data from this study by was presented in the previous section.

The next study to be examined is that conducted by Vosen et al. (1999) This study was of particular interest because it specifically focused on comparing and contrasting the costs of hydrogen storage as compared to battery storage technology. One of the first statements that they make is that hydrogen is preferable to batteries because of the large amount of storage that would be needed. They state that for a stand alone energy system, roughly a month’s worth of storage capacity should be needed. (Vosen et al., 1999, 1140) This would cause the cost of battery storage to double the $20,000 a year obtained in my calculations. The storage costs calculated by this study put hydrogen at $0.96/kWh and batteries at $4.69/kWh, a huge cost differential. (Vosen et al., 1999, 1146)

This study also raises another interesting possibility, a hybrid system consisting of both battery storage and hydrogen energy storage. This allows the system to take advantage of the high efficiency battery for the diurnal intermittency but rely on the hydrogen when the battery technology is not up to snuff. This option could have
important implications for the future development of renewable energy and its ability to meet the demands of an average household.

9.5- Hybrid System

The concept of the hybrid system throws an interesting new angle on the question of energy storage; there might not be a direct competition between the technologies. Might it, in fact, be possible that the two would actually be able to work together synergistically? Once the matter has been broached it almost seems to make perfect sense. Each technology has its strong aspects. Batteries are highly efficient over short periods of time and are fairly cheap as long as they so not need to supply a large amount of storage capacity. Recall that two days of storage capacity with batteries would be cheaper than a fuel cell system. But because all of the expense is in the storage itself as soon as larger storage capacities are needed then the costs skyrocket. Batteries are not incredibly attractive as a stand-alone energy system storage technology because it would simply be too expensive to provide two to four weeks of capacity in the form of batteries.

The other technology, hydrogen, has two major faults. It is not terribly efficient at capturing and releasing electricity, which leads to resource and expense problems for the renewable power sources being used, and additionally while the storage itself is cheap the other components required to produce and utilize the hydrogen are not, presenting a significant initial cost. On the upside, the long life of these components compared to batteries makes their cost somewhat less when examined on a yearly basis. Additionally hydrogen storage is capable of feats that batteries are not. Primarily, it is capable of
storing large amounts of energy at relatively little additional cost compared to storing small amounts of energy. The efficiency loss over time is essentially zero, unlike batteries, which will leak their energy over time.

So with two systems, each of which is capable of covering the major flaw in the other, what is keeping them from being used in conjunction with each other? One concern might be expense and space, but batteries are only expensive and bulky when they need to supply a large amount of storage capacity to the system. The hybrid hydrogen/fuel cell and battery system works by relying on the battery for usual diurnal intermittency and using the fuel cell system only when the diurnal battery system is not able to handle the loads being placed on it. (Kelouwani et al., 2005, 392) Because the battery system is being designed to only handle the day to day fluctuations and intermittency, it can be relatively small, approximately the size of a single day’s worth of backup capacity. The hydrogen system would be in place to cover those times when seasonal intermittency in effect and the system is consistently not producing enough power on a daily basis.

The hybrid system is essentially the same as the hydrogen fuel cell storage system, only with a few batteries added into the mix. The cost for the hydrogen side of the system would be essentially the same as the storage system that relied on the hydrogen alone. The battery system would be fairly inexpensive because it would only need to cover a few kWhs of capacity. The advantage to all of this is that the batteries will be the storage option that is utilized most of the time, with the hydrogen only being relied upon in when it is needed. This will allow the system to take advantage of the
higher efficiencies of the batteries for most of the power use. So while the cost of the hybrid storage system might be slightly higher than the cost of the hydrogen storage system, it will be quite a bit more efficient. (Ghosh et al., 2003, 477)

A hybrid system’s efficiency will be good for general conservation ideals and environmental sustainability but it also means that the production capacity of a renewable energy system can be significantly less than it would have to be for the hydrogen storage system. Since renewable production systems represent a significant cost, comparable to the cost of the storage system, reductions in the required size of these systems would represent significant savings. So even though the cost of the hybrid storage system would be higher than the hydrogen storage system, the overall cost of the entire system would actually decrease.

Vosen et al. (1999) estimate that the cost of such a hybrid system would be significantly less than either hydrogen or batteries alone. They estimate that the cost of a hybrid system would be 48% the cost of a hydrogen fuel cell system and only 9% of a battery based system. (Vosen et al., 1999, 1155) While such a system would still be more expensive than the rates given by our current energy system, the price would continue to drop as fuel cells and other hydrogen components continue to decrease in cost as they are expected to do (Khan et al., 2005, 843)

9.6- Economic Conclusions

In the physical world, batteries seem to have the dominance over hydrogen based storage technologies. There are exceptions, certain situations where hydrogen could
accomplish tasks that the batteries either could not or were not particularly suited to, but
for the most part the high efficiency that is offered by batteries simply beats hydrogen. At
the end of the chapter on technological capability it was suggested that the best way to
deal with the problems batteries had would be to find an alternative technology that could
supplement the battery technology, or reduce the number of batteries needed to cover
long term storage and seasonal intermittency as a means of making batteries more
feasible as our preferred energy storage technique, such as resource diversity to mitigate
seasonal intermittency or central storage options that would be efficient and cheap on a
larger scale. In areas that could not use these options, they could use hydrogen or
batteries depending on which was better suited for their needs.

In this chapter, which was obviously focused on economics and the social world
rather than the physical world, once again a technology seems to dominate over the other.
In this case hydrogen appeared to be preferable. With low costs for the actual storage and
moderate costs for the other components, hydrogen storage systems are less expensive
than the battery storage systems, which had relatively high costs for storage capacity and
no costs for other components. This leads hydrogen based storage systems to be far
cheaper than battery systems anytime that more than a couple of days of back up storage
are needed. Once again, there are exceptions.

A battery system will be cheaper in scenarios that require only a day or two of
back up storage, either because of low levels of intermittency or because reliability of
power is not important. They would also be preferable in situations where demand is
relatively low compared to the average American household (not a difficult feat to
accomplish). A few days of storage capacity for an American household might equate to several weeks of storage capacity in other cultures. But most sources agree that for a household in a developed country, two to four weeks of back up capacity would be required and to provide that level of back up power the cost for batteries would be far more than almost anyone could afford.

This finding put hydrogen back in a somewhat favorable light. It might not be the best storage option technologically, but at least it might be affordable and able to do the tasks required of it. But in the end, the option is presented that solves both the physical and the social problems associated with energy storage or at least it improves their ability to work within the real physical world and the real social world. The solution to the quandary whereby one technology seems to work physically and not socially and the other works socially but is not preferable due to its physical lacking is to use both technologies in a hybrid system.

The hybrid system ends up being a compromise in the physical world, using the more efficient battery technology when it can and relying on the less efficient hydrogen when it is needed. But in the social world, in terms of economics, a hybrid system can hardly be called a compromise because it does not meet in the middle. The hybrid system does not cost somewhere between the relatively cheap hydrogen and the prohibitively expensive batteries, instead it actually costs less than either. (Isherwood et al., 2000, 1019)
Chapter 10

ENVIRONMENTAL IMPACTS

While some of the environmental effects of both battery storage of energy and hydrogen based storage of energy have already been discussed, these have primarily been the issues relating to the efficiencies of the two technologies and how that would cause the primary source of the pollution to be used more, creating higher levels of pollution just because of the fact that the energy is being stored at all. While this is an important part of the equation, we must also examine the environmental effects and the safety of the storage technologies themselves and determine whether or not each of the two technologies would cause any specific harm to the environment or to the health and safety of the people using these technologies.

One of the most important things to consider when looking at the possible environmental effects of the storage technologies is that while the technology may not seem harmful at first, it may end up being harmful when it is being used in large amounts over long periods of time. The combustion of fossil fuels was not a problem for the environment until it started occurring in large amounts eventually leading to the rapid buildup of greenhouse gasses. What may seem benign while looking at a single unit may be less so when everyone in the US or in the world is using one.
Any environmental problems associated with batteries and hydrogen energy storage solutions are likely to be similar to the climate change problem in that respect. Benign and harmless in small amounts but the environmental problems may present large unforeseen problems as they achieve greater market penetration. It is vital that this sort of problem be discovered earlier rather than later, as it will be far easier to do something about or to look for alternatives at an early stage rather than a later stage. Additionally, it may be that there are health hazards associated with the technologies that people will need to be informed about so that the potential for injury can be minimized and the reputation of the technologies remain fairly intact. Hydrogen in particular must be examined for potential health hazards to determine the truth as to how safe it is and how it may be safely handled.

10.1- Batteries and the Environment

There are a few areas where batteries could have potential negative impacts on the environment and on human health. Batteries are composed of components that are almost all hazardous to human health. (Schaber et al., 2004, 23) Essentially every part of the battery except for the cover would injure a human who touched it, potentially severely. It is the causticity and the toxicity of their components that make batteries dangerous and give them the potential to harm the environment. In terms of resource use, emissions, or other potentially harmful aspects they are relatively benign and would be unlikely to harm the world at large.
The primary components of the classic lead-acid battery are exactly what one would suspect: acid (sulfuric) and lead. The acid component of the batteries is only dangerous if someone comes into direct contact with a concentrated amount of the acid, especially if the acid got into the eyes or the acid fumes got into the lungs. If batteries are used properly, the risk of acid exposure is relatively minimal. Modern batteries are often sealed and require very little maintenance and at most times the batteries would be kept out of contact in a secluded area where a person would be unlikely to even see them, let alone touch them. Should any acid find its way into the environment, it would be unlikely that it would be in high enough concentrations to cause any serious problems and should quickly be diluted or naturally react with calcium and other minerals, neutralizing in the process.

The component that has the greater potential for harm, in the long run anyway, would be the lead plates that are used in the batteries. Lead is well known for the problems it can cause to human health, from immediate poisoning caused by extreme exposure in a short period of time to the developmental problems it can cause in gestating babies and growing children. As a heavy metal, lead is difficult to remove from biological systems and has high levels of persistence. Should the lead from the batteries find its way into the environment, even in trace amounts, it could cause developmental problems in children and creatures in the ecosystem.

The successful management of this risk depends heavily on the handling of these materials, particularly when batteries have expired. Battery recycling programs for expired or broken lead-acid batteries used in cars have had a relatively high success rate
in retrieving and recycling the lead from these batteries. (Schaber et al., 2004, 23) Recent increases in the consumption of lead for the battery industry has had a corresponding drop in lead in the environment due to increased controls and protections. (Moseley, 1996, 85) If batteries are to be used in large numbers and need to be replaced every five years or so, then there will need to be strict rules regarding the disposal and recycling of the batteries to ensure that as little lead as possible enters into the ecosystem. This sort of program will also reduce the need for the extraction of lead from the environment, preserving the resource and saving money and energy.

Recycling programs will likely minimize the health and environmental impacts that are caused by batteries, at least in the short term. Over the long term, continued research should go into alternate battery models that rely on less toxic substances. Such batteries currently exist, but are more expensive than the lead acid batteries and they are newer technologies that do not have as much industry already built up around them. Advancement in the field of battery storage may well soon yield a replacement for the lead acid battery that is both cheaper and safer. One final interesting note is that batteries produce hydrogen during their normal course of operation and occasionally that hydrogen gas can escape and cause fires to be ignited.

10.2- Hydrogen and the Environment

Hydrogen has the benefit of having no terribly toxic or caustic components involved in its energy storage cycle. Hydrogen itself is a gas that is not poisonous or caustic to living creatures and the fuel cells themselves are made of relatively benign
components. With an output of just water, fuel cells seem to be relatively environmentally harmless. (Rand and Dell, 2005, 3) There are two areas of concern however. The first and lesser of the two concerns is the availability of platinum, which is often used as a catalyst in PEM fuel cells. The second and usually more pressing concern is the fear that hydrogen will explode, potentially killing and injuring many people. The lesser of the two concerns may actually end up being the more important issue, although the public’s fear of hydrogen is a topic that will have to be addressed both in this thesis and in the world at large.

Platinum is a precious metal that is already somewhat difficult to find. There is concern that, if fuel cells begin to be produced in large numbers, this resource will quickly be depleted and that there may not be enough to meet our needs. (California Energy Commission, 1999, 9) Aside from the increase in industrial activity required to extract more platinum, the main concern is that our supply of the metal will quickly be consumed and then there will not be enough for this purpose and its other uses. Currently alternatives to platinum for catalysts are being investigated, but this is still one of the primary catalysts used and is certainly the dominant technology. Further research must go into finding replacements that are economically and technologically feasible.

The larger concern with hydrogen as a common energy carrier is that it will be a danger to human life and valuable property. Images of the ill-fated Hindenburg disaster and the development of hydrogen bombs seem to have created a popular image in people’s minds that hydrogen is an explosive gas that is extremely dangerous. Nearly every time I explain to a person what I am writing this paper on they ask me the same
question, “Won’t hydrogen blow up if anything goes wrong?” This is a fear that seems to be nearly universal across the spectrum of people in this country. (Rand and Dell, 2005, 3)

Hydrogen is indeed a flammable gas. Like any substance that can be used as a fuel, it is high in energy and there are always risks associated with its storage in large amounts. However, what must be examined is not the question of whether hydrogen is completely safe or not, but rather how safe is it in comparison to the fuels and energy sources that it would be replacing? All experiments and safety tests seem to indicate that hydrogen is safer than gasoline and many other fuels. (Ogden, 1999, 266-267; NAS, 2004)

To begin with, hydrogen does not naturally explode. It does burn, but not with any concussive force. (Rand and Dell, 2005, 3) Hydrogen bombs and the types of explosion they incur cannot occur under normal circumstances. They can only be produced intentionally and with a great deal of difficulty. The reaction that occurs is a nuclear reaction whereby the hydrogen molecules undergo fusion, combining with each other to release large amounts of energy and they become helium. This reaction can only occur under intense pressure and heat, like in the sun or with carefully arranged explosive devices. Burning hydrogen is safe enough that creating and burning the gas is a common high school experiment done across the country.

Hydrogen is safer than gasoline because it is not explosive, like gasoline vapors are, and because it is highly diffusive and light. Because it is such a light gas, it tends to naturally dissipate rapidly and it does not collect in areas like gasoline vapors or natural
gas might. Instead it floats away when it is leaked. (Rand and Dell, 2005, 3) Thus it is unusual for enough of the vapors to collect to be easily ignited. If this should happen, then as has already been mentioned, the gas will burn but not explode, unless the gas is ignited while compressed.

Hydrogen could combust and cause injury people, but the same could be said of any fuel and it is far less likely to occur with hydrogen than with most of them, especially gasoline or natural gas. This is another reason why it might not be a good idea to use hydrogen on the premises of a household. While it is at least as safe as gasoline, the average citizen would not want to keep a large amount of gasoline on their property, even though they are perfectly willing to use it on a daily basis. A central storage option for hydrogen, with electrical production occurring from that hydrogen at the central premises would be a safer option, in addition to being more economical and efficient, if hydrogen is to be used at all and central storage is an option. One large obstacle that the developing hydrogen infrastructure will have to overcome is the fear of hydrogen that is so evident in the average citizen. This could be accomplished through educational programs and through demonstration projects that would eventually accustom a person to the concept of hydrogen as an everyday fuel.

10.3- Energy Storage and the Atmosphere

Near the beginning of this thesis, it was mentioned that one of the largest impacts that will occur because of human activity on this world will be the rise in temperature caused by the combustion of fossil fuel, which releases greenhouse gasses, particularly
carbon dioxide into the atmosphere. It is difficult to determine the implications of battery technology and of hydrogen and fuel cells for the global climate change issue. This is because neither of these technologies actually produces carbon dioxide by itself. Instead, they are capable of increasing the amount of greenhouse gasses that are produced during the creation of electricity. Because of the efficiency losses, any electricity that is made from a carbon-based fuel and then stored in either technology will automatically produce more carbon dioxide and other greenhouse gasses than it would if the energy were never stored at all.

Batteries may end up being better for the atmosphere for two reasons. The first reason is that they are more efficient than the hydrogen fuel cell systems, so less carbon-based fuels would need to be used to create the same amount of retrievable stored energy. This in turn would create fewer greenhouse gasses. The assumption in this case is that the same fuels are being used to produce energy for storage as hydrogen as for the batteries. Hydrogen currently mostly comes from natural gas when it is produced from fossil fuels, while electricity stored in batteries could come from a number of fossil fuel sources, such as natural gas or coal. If coal was being used to generate electricity to store in batteries, then hydrogen may end up having less carbon released into the atmosphere, unless large strides are made in carbon sequestration technology. (Rand and Dell, 2005, 4)

The difficulty in determining which one would have a better impact on the atmosphere really arises from the fact that there are many different options for where the electricity to be stored can come from and if hydrogen is being pulled directly from a fossil fuel rather than being created through electrolysis. If we assume that the same
energy feedstock is being used to store energy in batteries or as hydrogen, then the batteries will have fewer greenhouse gasses, just due to their efficiency.

The other reason why batteries are less likely to lead to an increase in greenhouse gas production is because batteries are far less likely to be used to store energy from fossil fuel sources than hydrogen. In fact, hydrogen can even be seen as encouraging the consumption of fossil fuels because they would be such an inexpensive and available feedstock. Additionally, the conversion of fossil fuels to hydrogen increases the utility of those fuels in many situations by making them more portable and usable while converting these fuels into energy stored within a battery gains those advantages in only a few situations. The only situation where a fossil energy source would be stored within a battery to any benefit to the user might be in an electric vehicle that fed off of a grid powered by fossil sources. There would be no reason to have batteries in other situations that were fossil fuel based because the utility would not increase and the cost would rise. For hydrogen, on the other hand, the conversion of a fossil fuel into hydrogen makes it more mobile and more usable for a variety of purposes. Because of this, hydrogen is more likely to have a negative impact on our environment than batteries would because the likelihood of a continued utilization of fossil fuels as a primary energy source is greater when hydrogen is used as a storage medium than batteries are. (Dunn, 2002, 252)

The environmental benefits of hydrogen as an energy carrier are nebulous, at best. Yet there is the potential for hydrogen to aid in the greening of our energy industry, but it will not automatically do so. In fact, there are many scenarios in which the use of hydrogen actual makes our energy-environment relationship worse. It depends entirely on
the source of the hydrogen exactly how environmentally friendly the hydrogen is and the net effect it will have on our environment.

Since hydrogen can come from all of the common fossil fuels, a number of biological sources, and even pure water, there are many different levels of how ‘green’ it will be. Only one pathway will actually have a net benefit for the environment unless major strides in carbon sequestration are made, namely, the production of hydrogen through the electrolysis of water using clean renewable resources, like solar or wind. If the hydrogen comes from the reformation of fossil or biological fuels, at the very least carbon dioxide will be emitted and likely other pollutants will as well. (Consonni & Vigano, 2005, 702) Reformation is an energy intensive process that takes a fuel and pulls out the hydrogen. Energy is being lost in two ways in this process.

Firstly the resultant hydrogen has a lower energy content than the original fuel. If that fuel had just been used more energy would have been produced than would be produced by using the hydrogen from it. Also it took energy to break down the source fuel, energy that could have been used directly. Thus the same pollutants have been produced to get less energy. Using hydrogen from these methods will only increase our pollutant output because our energy use will stay the same, meaning that more pollutants must be produced to meet that demand. The same thing applies to hydrogen produced by electrolysis using conventional fuels. Hydrogen produced by burning coal to produce electricity to run the electrolysis will yield less energy in the form of hydrogen than was present in the form of coal. Once again, the same amount of pollution is produced to yield less energy.
The laws of thermodynamics demand a reduction in the usable energy available with each power transfer, so any method of producing hydrogen that also produces pollution will be, by default, more polluting than simply using the source of energy for breaking down the hydrogen for an application instead of the resultant hydrogen. Instead of turning methane into hydrogen to use in a car, just use the methane in the car. Instead of using coal to produce hydrogen to provide electricity, just save the coal and use it when needed to produce the electricity. Hydrogen should only be used, will only have environmental benefits, when it is assisting the development, deployment, and feasibility of a renewable energy system by providing services that the renewable energy source could not accomplish without its use, and it should be used as sparingly as possible.

10.4- Environmental and Safety Conclusions

Neither battery storage nor hydrogen storage of energy seem to have any real advantage over the other in terms of their environmental or health impacts. Both technologies seem to have some resource concerns that could be solved either through intensive recycling programs or through the search for possible substitutes. Additionally, both technologies have the potential to harm human health. They are composed of substances that can naturally be dangerous, hydrogen through burning and batteries whether through lead poisoning or acid burns. While they do have their inherent dangers, so would any storage technology, fuel, or energy carrier.

These dangers are already less than the dangers presented by out current technologies. The electricity in our walls, gasoline in our cars, and natural gas in our
stoves have injured countless people but the effects are minimized through safety regulations and these fears are pushed to the back of our minds because, while they are not every day experiences, accidents are relatively commonplace. Batteries are already found in nearly every household, and while people do suffer from battery related injuries, we rarely hear about them. Hydrogen, on the other hand, is relatively unfamiliar other than as an H on the periodic table. The only real experience and exposure people are likely to have to hydrogen would be the Hindenburg or the H-bomb

Any energy storage technologies have the potential for danger, hydrogen and batteries certainly do, and for environmental damage. But the dangers they present are minimal compared to the dangers we already live with every day and with the damage that is already occurring to our ecosystems. With the proper guidelines, regulations, and common sense they could be nearly entirely benign to the human existence and to the environment, leaving the majority of the impact to our lives and to the environment to the source of the initial energy.
Chapter 11
CONCLUSIONS

The purpose of this paper was to examine the storage options that will be available in the near future and how they might interact and develop in order to support a renewable energy system. It was determined that these storage options will play an important role in the ability of intermittent renewable energy resources to enter into our energy system. By storing the energy from the intermittent renewable sources it is possible to force them to behave with the same energy quality and reliability that is accustomed to with conventional energy sources. The conventional sources are able to supply energy when it is needed in the quantities that it is needed, while renewable energy is bound to the physical availability the natural world provides for us. Solar energy is a wonderfully clean source of power, but it not available at many of the times that we would desire it, and it may produce a significant amount of power over the course of an entire day, but it is not particularly useful if our power need is for a large amount of power over the course of an hour and very little for the remainder of the day. The storage of energy from renewable power sources allows for the shifting of the distribution of the renewable power availability in time. By doing this, intermittent sources of power can behave like our conventional power sources which can be turned on and turned up at the will of the users.
Storing large amounts of energy is not a simple task, however, and adding storage to an electrical generation and distribution system has a number of technical and economic effects that can alter how a renewable energy source performs. The obvious effect is that adding an energy storage system will increase the price of the already expensive renewable energy systems. Additionally, due to the laws of thermodynamics, when the energy is stored and released some of it must be lost, which means that larger renewable power systems may need to be built to account for the loss of power that will occur through storage. There are also questions on whether or not the storage systems will take up huge amounts of space that may not be available and questions about what sort of environmental effects the storage systems themselves might have beyond the effects of the initial source of energy.

Because the storage technology so powerfully affects the nature of the renewable energy system and how feasible it might be to implement, this thesis was designed to examine the two technologies that currently show the most potential for meeting the needs of renewable energy storage. The primary focus for the discussion was on the development of renewable energy for the use in homes, businesses and in transportation with a focus on the activities within the United States, though some mention of renewable energy use in industry and foreign countries was also included. The two technologies were deep-cycle lead-acid batteries and hydrogen for use in fuel cells. The two technologies were examined along the criteria of the effects that a storage system would have on the renewable energy system that were discussed above and also on how they would fit in with meeting the three primary goals of shifting from current energy system
to a new one: economic independence, energy security, and environmental stability and health.

The end result of this examination and comparison of the two technologies was that each would likely have a place within the new energy system and that using the two together in a hybrid system could yield the technological benefits of both and would possibly be less expensive than using either one on its own. The two aspects of the storage systems that ended up playing importance in this result were the efficiencies of the systems and the costs of the systems, although batteries had some technological limits that keep them from ever being able to perform certain functions, primarily their inability to recharge quickly.

Efficiency greatly effects both cost and environmental impact, so it was determined that the storage of energy should be as limited as possible, and that mitigation of the intermittency of the energy systems should be attempted to as great a degree as possible. But since it would be quite difficult and costly and maybe even impossible to eliminate all intermittency from renewable energy systems, it is likely that some energy will have to be stored at least some of the time in an energy economy based off of renewable energy technologies. Because the efficiencies of battery systems are so much greater than the efficiencies of hydrogen fuel cell systems and efficiency plays such an important role in determining many aspects of the renewable energy system, batteries should be used as often as possible except in a few situations where hydrogen would be preferable due to certain aspects of its technological nature which give it some advantages over the more efficient battery systems.
Batteries are technologically limited by the amount of time it takes for them to recharge. While this doesn’t particularly affect the production and storage of power for homes and other buildings, it does affect the transportation industry where vehicles are often required to run for lengths of time and distances that would exceed the capacity of a vehicle's battery system without the time to recharge. The times when the battery would not suffice, when there would not be several hours to recharge would be those times when a vehicle was traveling great distances or for long periods of time. Examples in the private world would be driving to another state for a vacation or a few people who had exceptionally long commutes. More common examples can be found in the public and commercial worlds. Busses that travel all day, trucks carrying goods great distances, ships, taxis and other such vehicles that must be able to run for 8 hours or more a day could not logistically rely on batteries. For these situations, hydrogen could be used because, instead of a several hour recharge time, a hydrogen vehicle can refuel in a few minutes, comparable to the time spent at a gasoline pump for refueling. (Suppes, 2005, 114) Most other times the battery system would be capable of supplying their transportation energy needs. But for public transportation vehicles, commercial transport vehicles, and some private fleet vehicles, longer run times will consistently be needed and taking a few hours to recharge once the initial storage capacity has been utilized would be out of the question.

In these scenarios, the quick refueling offered by hydrogen would allow these vehicles to operate in a renewable energy environment the same way they do on gasoline. One solution to determining the storage option available on vehicles would be to offer
battery powered cars for people who would rarely exceed the range of the batteries, fuel
cell vehicles for cars that would routinely exceed the range of a battery, and hybrid
battery-hydrogen vehicles that would allow a user to decide what power system they
would use that day depending on what they required of their vehicle. The hybrid option
might be of service to a person who travels long distances once or twice a week but on
the other days only travels short distances.

The other areas where hydrogen would end up being required would be in the
long term storage of large amounts of energy, primarily to deal with seasonal
intermittency where a month or more of back up power may need to be stored. Because
the price of a battery storage system is directly proportional to its storage capacity, large
battery storage systems are quite expensive. The cost of a hydrogen power system is only
partially related to the amount of storage capacity it has, with the storage being relatively
inexpensive and the other components of the system providing most of the cost. A
hydrogen system that can store a month’s worth of backup power is only slightly more
expensive than a hydrogen system that can provide a day’s worth of backup power.

In most situations and at most times of the year, having a day or two’s worth of
backup power would satisfy a user’s needs. Seasonal intermittency, however, creates
scenarios where a daily deficit of energy might occur for weeks or months at a time, and
while the deficit might be small it would quickly drain a day or two of backup and then
there would be no ability to fill in the deficit of energy being provided by the renewable
energy system. Thus a large amount of energy is needed to be stored to deal with
seasonal intermittency.
Hydrogen energy storage systems are still inefficient and somewhat expensive, so alternative options should still be sought out. Areas that already have connections to a regional energy grid have the most options. Through a grid, an area under the effects of seasonal intermittency could import energy from areas that either are not suffering from intermittency at that time because they either rely on different energy sources or because their geographical locale is different enough that the same energy source that you use is available there when it is not in your area. If this is not possible or not desired, then there are central storage options that are available that may be more efficient than a hydrogen system.

Even if the alternative large-scale central storage options are not available and hydrogen must be used, having a large-scale central hydrogen storage and fuel cell stack to provide grid electricity may be more efficient or at least less expensive because then every household would not be required to purchase and maintain their own hydrogen fuel cell storage system. Under these scenarios, the utilities would become more like power managers rather than power providers, collecting and storing energy when a household is producing a net surplus and releasing that stored energy when a household is producing a net deficit that their battery storage could not handle. It may be that, if distributed generation increases in popularity and becomes the way that much of our power is produced, the utilities will cease much of their production of power and become more of a storage and distribution entity. In a sense, they would maintain their role of managing the power available on the grid by monitoring how much energy the sum of the houses on their grid were producing and by releasing or storing energy with their large central
storage technologies as too little or too much energy is produced by the distributed generating technologies.

In households and areas that are not connected to a regional grid, a hybrid storage system consisting of a day or two of storage in the form of batteries and a month or two of storage capacity in the form of hydrogen on the premises would allow these households to rely on the renewable energy sources that are available to them without having to worry about diurnal or seasonal intermittency and without having to pay the high cost of large amounts of battery storage. By relying on batteries to handle most diurnal intermittency and short-term intermittency, the higher efficiency of the batteries can be used to store and transfer most of the electricity that needs storing. The backup small-scale on-site hydrogen storage, large-scale central hydrogen storage, or other large scale central energy storage options will give the ability to have large amounts of back up energy at low cost, providing higher security and handling seasonal intermittency.

It is in these two areas, vehicles with long daily running times and in handling intermittency which small-scale battery systems cannot handle, where hydrogen seems most suited and where its unique abilities would provide a net benefit despite its lower efficiencies. It should be attempted to cover all other areas of energy storage through batteries, mitigation of the need for storage, or other high efficiency large-scale energy storage options. The hybrid systems are far more efficient than the hydrogen systems and seem to be less expensive than relying on either hydrogen or batteries alone, but they are still not the optimal choice for energy storage.
With these lines laid out of which storage option would be preferable for different storage needs, the governmental policies that are being implemented to encourage the development of a new energy system should reflect this idea of one storage option for one need and another for a different need. While the natural market should encourage the growth of an efficient system that would be less expensive due to those efficiencies, the energy market is far from a natural market. Instead the energy market is grossly distorted by incentives, subsidies, and special interests designed to promote the will of the legislature. Sometimes these incentives promote environmentally sound options and other times they do not. Currently there is a large push for the development of a hydrogen infrastructure and the growth of a hydrogen economy by federal, state and local governments.

While this could be good, it might very well be detrimental. The policies and incentives that are currently going into place tend to give a carte blanche acceptance to the development of a hydrogen energy system. The policies push hydrogen for many storage uses where hydrogen might not be optimal and they place little emphasis on how green the hydrogen actually is. With the current push for hydrogen, it is quite possible that hydrogen will actually cause the consumption of our fossil fuels to increase rather than decrease and to production of carbon dioxide to increase similarly.

The government needs to develop policies that will support the development of a renewable energy system in general, rather than specifically placing so much attention on hydrogen. The policies for the new renewable energy system should include policies and incentives that promote both batteries and hydrogen, but the policies should try to target
these two storage options in a way that pushes them into their optimal roles within the
energy storage system so that they are used in the combination that yields the maximum
environmental and economic benefit. Additionally, it should strongly stress the concept
of hydrogen from renewable sources rather than from fossil sources in the medium to
long term, using fossil sources only as a steppingstone in the short term to more
effectively and smoothly transition to renewable hydrogen.

Both hydrogen and batteries have a purpose and a use where they would be
optimal in the development of a larger renewable energy system. It is vital, however, that
the two storage options be used only in the areas where they are suited in order to
maximize both efficiency and cost. A failure to focus the development of these storage
options within their proper areas could lead to costs that are far above what they need to
be, waste, and possible environmental degradation. The policies of the future should bear
in mind that while markets may be altered and distorted, and popular opinion may sway
to and fro, the laws of thermodynamics and nature are set in stone and not subject to the
vagaries of the social world and the human mind.
Chapter 12

POLICY CONSIDERATIONS

Assuming that a new energy system did arise, one that relied on hydrogen as a fuel carrier in part or full, there are a number of issues that would need to be addressed. Firstly, the question of efficiency and when hydrogen should be used must be handled. Additionally, the question of how ‘green’ the system is must be examined. Associated with both of these questions is the issue of the transition between one economy and the next and how it might be accomplished and where it might (or should) end. The final issue is that of cost, and how to make this new system competitive with the old in the marketplace.

It is vital that action be taken quickly, because the new energy economy is already beginning to emerge and many of the vital questions have yet to be raised or considered by the politicians pushing it forward. (Dunn, 2002, 239) The idea seems good on paper but many problems need to be examined and alternatives considered. Most citizens are uneducated about the physics and chemistry of a hydrogen economy and thus do not see the potential dangers that lie in that road. Nor do most Americans realize that this clean burning fuel currently comes mostly from fossil fuels and heavy use of hydrogen could potentially increase emissions over current levels. The alternatives discussed here must be considered, as they rely less heavily on hydrogen and should provide the same technical utility that hydrogen offers, possibly at a lower cost.
Since a new energy system, to obtain all of the benefits desired, should rely primarily on renewable energy sources, and batteries, hydrogen, central storage options and all of the other options are simply ways of storing the energy gained from the renewable energy sources, the issue of highest importance is how can the initial renewable energy be used most effectively at a reasonable cost. With this in mind, the policies and incentives offered should be working along similar lines. They must push for a true change from our current energy infrastructure and set up the new one in a way that will provide the maximum environmental, economic, and security benefits at the most reasonable cost.

The area that will require the greatest amount of government oversight and guidance through policy and incentives will be in the field of transition. The current political climate almost ensures that the role of hydrogen is going to increase in the power sector, regardless of how beneficial it really is. Many government officials in the United States are pushing for the development of hydrogen highways and a fueling infrastructure that will allow hydrogen to replace gasoline as the fuel for cars and other larger vehicles. While I have already stated that policy and incentives should try to limit the role of hydrogen to areas where it is absolutely needed in preference to batteries and central storage options, the fact is that hydrogen will likely play some role in our future energy system and policies will be needed to guide its development along the most environmentally beneficial pathways.

There are three possible futures that seem possible for hydrogen: a marginal hydrogen economy, a fossil fuel hydrogen economy, and a green hydrogen economy.
Each of these futures follows the ones preceding it, beginning with the marginal hydrogen economy and ending with the green hydrogen economy, but the transition through these economies could end at any time through the progression. It is vitally important that hydrogen be guided through these stages so that the end result is an energy system that attains the dreams and hopes that we have for our new energy system: improved economy, environmental benefits, and security.

The first stage is where we currently are, the marginal hydrogen economy. At this stage hydrogen is just starting to make an appearance on the market place as a fuel and it is being used in a few metropolitan areas. However it is still difficult to get hydrogen in many areas and the locales that do have hydrogen available are not linked to other areas that offer hydrogen. This makes hydrogen-based travel between them difficult or impossible. The overall use of hydrogen in this stage will account for only a few percent of the overall energy use or less. Additionally no codes or standards between the regions has as of yet been agreed upon, which may make linking these systems difficult and it is unclear what standard if any will become universal. (Dunn, 2002, 237)

The next stage will be the fossil fuel hydrogen economy. This stage of the hydrogen economy is marked by the source of the hydrogen, fossil fuels and carbon intensive biological fuels. Currently more than 90% of the hydrogen produced in the US is from natural gas reformation and by all indications it will remain that way for the near future. The fossil fuel hydrogen economy differs from our current situation in the amount of our end energy that comes from hydrogen, which in turn comes from fossil or carbon
fuels. This stage would be when about 10% or more of our energy use was in the form of hydrogen and the majority of our hydrogen came from carbon-based sources.

By this point it is likely that the regions will have been linked allowing hydrogen use in most areas and allowing hydrogen travel between regions. Hydrogen will now have supplanted a significant portion of our other fuels making our energy system more secure and improving our economy by keeping dollars within our borders. The fossil fuel hydrogen economy will not, however, be benefiting our environment for the reasons listed earlier in the paper, in fact it will have possibly made the environmental situation worse as more fossil fuels will be consumed. The reason it will be adopted after the marginal hydrogen economy is because so much of the infrastructure that would be needed for it is already in place, from the natural gas production and transportation systems, to the industrial steam reformation plants.

The final stage in the development of a hydrogen economy would be the green hydrogen economy. The difference between this and the fossil fuel hydrogen economy would be purely in the source. Hydrogen would now be produced without the use of fossil fuels, either as a feedstock or energy source. Instead they would rely on clean renewable energy sources. This last stage would garner the positive environmental effects of a hydrogen economy along with the security and economic benefits of the fossil fuel hydrogen economy.

Since it does appear that hydrogen will have a place within our future energy structure, primarily within the transportation industry but also within sections of the power production industry, an effort should be made to guide the hydrogen economy to
the most beneficial stage of its development and to do so as quickly as possible. The marginal hydrogen economy is relatively harmless, but it is not useful either. The fossil fuel hydrogen economy is good for security and economy, but it is actually worse for the environment than doing nothing at all. The stage that has all the benefits and none (or at least few) of the detriments is the final stage, the green hydrogen economy.

While it may be possible to achieve this economy by moving directly from the marginal to the green hydrogen economy, that would be very difficult and would not take advantage of the market place and the natural growth of the hydrogen economy that might occur by going through all three stages. Thus attempting to skip might be more expensive and take a longer period of time, during which we would be stuck in our current system. Instead efforts should be taken to ensure that the fossil fuel stage occurs but is in place for as short a time as possible before moving on to the green hydrogen economy. In essence, the fossil fuel stage should be used as a steppingstone to more easily get to the green stage. (Dunn, 2002, 237)

In order to accomplish this, governments must plan to make that transition within a relatively short period of time, within 15 years or so of achieving the fossil fuel economy and preferably sooner. Incentives for the production of hydrogen from fossil fuels should all be set to expire or lessen within that time period while incentives for renewably produced hydrogen should be ramped up to encourage that method. While at first all hydrogen could be designated as a green fuel, that classification could be revoked from fossil fuel based hydrogen.
The encouragement of the fossil fuel hydrogen economy will spur the growth of the overall hydrogen infrastructure, lowering the costs of the various components and by creating a supply for the demand to grow on. By relying on our capabilities to produce and transport hydrogen from natural gas we will be taking a head start on the development of a hydrogen infrastructure and will more quickly be ready to transition to a green hydrogen economy. (Dunn, 2002, 238) The trick will be to ensure that we do not get stuck at this fossil fuel stage, as the environmental effects could be disastrous from lingering too long.

Additionally, research should be conducted to try and determine what situations would require or benefit from onsite hydrogen storage. This may occur in areas that are not currently connected to a grid and are remote enough that the expense of adding grid connectivity would be too high, in scenarios where a load profile has a high demand for short periods of time compared to their average demand, or where stability of electrical supply is of utmost importance and onsite production of energy or hydrogen as a backup would be more stable than grid reliance. In the average westernized household, it is unlikely that it will ever be necessary or economically beneficial, with the exception of a few remote areas.

There are a number of actions that the government should take to shape an energy system that will meet the goals of security, economic, and environmental improvement as compared to our current system. Without these policies as a guiding force, it is possible that the resultant energy system, brought about by hype and industry, will be would be more detrimental to our society and the environment than helpful, growing rapidly and
succeeding at its goals, but damaging the society within which it operates. These policies must be enacted quickly as the new energy economy is already developing as oil prices are rising and the development of a hydrogen based transportation system is beginning.

1. Discourage the use of hydrogen except in areas where it is needed. Tax incentives and government funding should be provided for fueling stations, but no long-term incentives should be provided for the hydrogen itself. This will spur the growth of the hydrogen infrastructure to fill a vital void but not artificially lower the cost of hydrogen. If hydrogen were very cheap, people would use it and not realize the natural inefficiency of its production. By ensuring that hydrogen remains more expensive than the electricity available, people will be encouraged to use that when it is possible.

2. In the short term, over the next ten to fifteen years, tax incentives should be provided for hydrogen produced renewably. These incentives should be designed to give an economic advantage to hydrogen made without carbon emissions over hydrogen from fossil or carbon based fuels.

3. Additional incentives should be placed on home renewable energy systems, such as solar panels or wind generators. Batteries (up to a certain storage capacity) should be eligible for these incentives as well. Alternative storage options like hydrogen and fuel cells should not be encouraged except in areas where grid connectivity is unavailable.
4. Research should be aimed at improving the efficiency of solar panels and the renewable energy sources. Improvements here will be more effective than improvements in the storage efficiency, which should take a secondary importance.

5. Additional research should be undertaken to examine how easy or difficult it would be to shift utilities away from a generating operation to just a storage and distribution operation. In essence, how could they shift into energy managers, storing excess energy over the long term and providing it when a home system simply just does not have enough power from either its power producing system or battery backup. This will ensure electrical stability in the short term without excessive storage capacity on the part of a homeowner and will also more efficiently deal with the problem of seasonal intermittency than an individual could. They would likely wish to keep some generating capacity online in order to absolutely ensure that they could provide the needed security. One or two plants could be brought online if the central stores of energy got too low.

6. Tax breaks should be given to vehicles that offer battery power as an option for their operation in addition to another fuel.

7. All of these incentives should not be designed to be permanent, rather they should have a set schedule, where they would lessen over time. This will encourage manufactures to begin or increase production, thus developing an economy of scale. At the same time it will not create a system of reliance on the incentives. Since their schedule of decline and eventual demise will have been laid out to
begin with companies will have to account for their disappearance and account for that in their business plans.

8. One area in particular that should be studied would be the level of battery storage capacity that would be economical for households based on their load profile. If it could be determined at what point additional storage capacity would no longer be a cost effective option compared to the addition of hydrogen storage or reliance on a grid delivered central storage option then money could be saved by purchasing the minimally sized battery bank. This would yield maximum productivity and use of the system for its cost.

By taking this range of policy options under consideration, it may be possible to guide the budding new energy economy into the proper directions. By minimizing the reliance on hydrogen over other storage options and assuring that when hydrogen is used in the long term that it is green hydrogen not polluting hydrogen we can develop an energy economy that is secure, economically sound, and environmentally friendly. These policy options are aimed particularly at the storage options of energy rather than the development of renewable energy systems, but storage is an important stumbling block that lies in the pathway of a renewable energy economy. Further developments, policies, and research will be required before the renewable energy economy will be economically and technologically viable.
REFERENCES


EIA Household Electrical Use Website.


Hera Hydrogen/product/Hydride Compressors Website.


Isherwood, William; Smith, J. Ray; Aceves, Salvador; Berry, Gene; Clark, Woodrow; Johnson, Ronald; Das, Deben; Goering, Douglas; and Seifert, Richard. “Remote Power Systems with Advanced Storage Technologies for Alaskan Villages.” *Energy*. Vol. 25. 1005-1020.


