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Electrical Grid Energy Storage Using Hydrogen: A Feasibility Study

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Abstract

In this project, we studied the possibility of implementing hydrogen as energy storage. With the focus being on decarbonizing the grid, we looked at studies that were powered by renewable sources. In addition to utilizing renewable sources, we decided to study electrolysis as a way to produce hydrogen. Electrolysis is the splitting of water to obtain hydrogen and oxygen, which is a carbon free technique. Pulling from two different papers, we were able to construct an equation that modeled the levelized cost of producing hydrogen. We also calculated the levelized cost of a fuel cell too, with hydrogen as fuel. After performing some analysis, we found that producing hydrogen by electrolysis would be very expensive, making it unsuitable for the market right now. We also found that the biggest bottleneck on the cost is the cost of electricity and the capital cost of the electrolyzer.

Keywords

renewable energy, electrolysis, fuel cell, sensitivity analysis, economic feasibility

Cover Page Footnote

Thanks to Professor James Doyle Thanks to Macalester's Physics and Astronomy Department

Electrical Grid Energy Storage Using Hydrogen: A Feasibility Study

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1 Introduction

There is an increasing need to lower carbon emissions in order to prevent irreversible climate damage. In response to this issue, renewable energy sources such as solar and wind have become popular on the market as energy generators. However, one limiting issue with these sources is that they are intermittent, meaning that they do not always match the demand of the grid. Batteries have been developed to store some of this excess energy, but they can only affordably store on a scale of hours and days, not months, which would be needed in order to fully implement renewable energy [1]. A sustainable solution is the use of hydrogen as a storage medium because it is the most efficient energy carrier (140 MJ/kg). Using hydrogen, energy can be stored for a longer period of time and used later when the demand is high. The hydrogen would be used in fuel cells, which combine hydrogen with oxygen to produce water and energy. This is a carbon free process as the only byproduct is water. Due to the pandemic, large companies are beginning to transition to renewables. The pandemic has had a lot of negative effects, but it can be an opportunity to restructure the energy sector and scale up clean hydrogen production. In order to reach the goal of being fossil free by 2050, we cannot wait until hydrogen production methods are entirely carbon free to implement them.

2 Background

A hydrogen industry already exists because hydrogen can be used to refine petroleum, treat metals and produce fertilizer which is important for the agriculture industry. However, the majority of today's hydrogen is produced by fossil fuels [7]. There are several different methods to produce hydrogen including steam methane reformation, partial oxidation, photolysis and electrolysis, and each method has its advantages and disadvantages. Steam methane reformation is currently the method used to produce 96% of the country's hydrogen but it has carbon monoxide and carbon dioxide as byproducts. Partial oxidation is another already established technology, but it produces heavy oil and petroleum coke which is a carbon rich byproduct material of oil refining. In terms of carbon free methods, photolysis and electrolysis have oxygen and water byproducts respectively, but the photolysis system has a low efficiency and the electrolysis system can be very expensive. We will explore these costs in this experiment [8].

Hydrogen is a very versatile fuel and because the biggest energy sector in the United States is transportation, hydrogen could drastically lower our carbon footprint. Even though it is in its early stages of research and development, the hydrogen economy could provide millions of jobs in the United States [8]. Shell gas has already established projects in Europe and China that produce hydrogen from renewables by electrolysis [9]. It is estimated that in 10 years hydrogen could earn $140 billion in revenue annually and provide up to 700,000 jobs in the United States. In addition to creating jobs within the country, hydrogen could give the United States more energy independence, mitigating its reliance on other countries for fossil fuels [2]. The feasibility of hydrogen is very dependent on the cost, which can be measured by the price of hydrogen per kilogram.

3 Literature Review

While researching for this project, we examined several studies to learn more about the feasibility of the hydrogen economy. To build our model, we focused on two studies done by Li et al. and Miao et al. [5][6].

In Li's study, they performed an economic analysis of three different paths. The first was hydrogen sold as a chemical material, the second was hydrogen fuel that could be used in a proton-exchange membrane fuel cell, and the third was hydrogen that was made to be burned. This study used valley electricity and curtailed electricity which are both forms of excess energy. The study found that utilizing this excess electricity could decrease the imbalance between production and consumption, reduce grid peak load, reduce trough-peak congestion, and encourage development of renewable energy distribution systems. They also found chemical storage to be reliable, highly efficient, compatible with the grid, and to produce zero emissions. Power used to compress hydrogen in this study was also supplied by renewables. Many experiments revealed that Economy of Scale applied to the size of the plant; therefore, the larger and more widespread the system was, the more the cost dropped. They found that water electrolysis was a clean sustainable method but it required a large supply of electricity so it needed to be in a place with lots of excess renewable energy. Recently, electrolytic material and fuel cell costs have become more affordable. Other costs such as how much they charged for peak electricity went into calculating the levelized cost of energy [5].

Miao also had three different pathways. The first was producing hydrogen that was injected into the gas pipeline, the second was producing hydrogen and combining it with carbon dioxide to produce methane, which already has infrastructure, and the third was producing hydrogen that was later converted back into electricity. Miao et al found that overall, the cost of these three different plants was greater than natural gas plants but that they would still have a smaller carbon emission footprint [6].

4 Our Model

Initially, we did some calculations to see if it were possible to replace the United States' methane with hydrogen. In the United States, methane is used in the electrical power, fuel, residential, commercial and transportation sectors. We discovered that it was extremely expensive to replace, on the order of 6 trillion dollars, and an unrealistic way to decarbonize the industry. Instead we invested the cost of producing hydrogen by electrolysis as a method to decarbonize the grid. It is estimated that the cost of electricity would need to be around $10-15/MWh (per megawatt hour) in order to make the electrolyzers competitive with steam reformation and around $50/MWh to be competitive with natural gas plants.

We generated our estimate for the cost of an electrolyzer-fuel cell pairing by reproducing a model created by Bin Miao and then adapting it with data from a study done in China by Y. Li. We preferred Miao's model because there were clear equations for the annualized cost and levelized cost of energy. We used Li's numbers because Li's process was most similar to the one we thought was likely to be implemented in the United States, selling hydrogen as a chemical material to be used in fuel cells. Li and Miao's studies examined the utilization of cheaper spillover energy to power electrolyzers, such as curtailed or valley electricity. Curtailed electricity is electricity that is excess to the grid for safety, economic or stability reasons. Valley electricity is excess electricity due to low demand. When looking at an energy demand graph, the times of high demand form peaks and the times of low demand produce valleys; these are the times when the excess energy could be used to power electrolyzers. In our model, we calculated the levelized cost of energy while adjusting the different parameters of the electrolyzer and the fuel cell. The parameters included the capital cost, the efficiency, the capacity factor and the cost of electricity.

5 Experiment

The equations for cost calculation and the variables used are defined below.

Cost of Hydrogen $C_H = CC \times CRF + F_{o\&m} + V_{o\&m}$

CC = the capital cost. We are modeling a 100 MW electrolyzer and used CC_{el} = \$340,000/MWh for the overnight capital cost of the electrolyzer. We also included the replacement cost in the capital cost term. 25% of the system is replaced about 3 times during its lifetime, which then gives

$$CC = 100MW \times CC_{el} \times (1 + 0.25 \times 3.57)$$

CRF = the capital recovery factor which is $\frac{i(1+i)^t}{((1+i)^t-1)}$ with i = 0.08, the discount rate, and t = 25, the lifetime of the electrolyzer, two numbers we got from the Li paper.

$F_{o\&m}$ = the fixed operation and maintenance cost, 5% of the capital cost.

$V_{o\&m}$ = the variable operation and maintenance cost. In our case this appears to be dominated by the cost of electricity, which we set at \$40 per MWh.

The cost of hydrogen gives us the price needed in order to produce one

MWh of stored chemical energy. From there we applied these equations to the fuel cell, using the cost of hydrogen from above as the fuel cost ($V_{o\&m}$). For the fuel cell, we have
Fuel Cell Annualized Cost $FCA = CC \times CRF + F_{o\&m} + C_H$

We are modeling a 100 MW fuel cell and used CC_{fc}= \$500,000/MWh for the overnight capital cost of the fuel cell. We also included the replacement cost in the capital cost term. 30% of the system is replaced every 5000 hours, so for a 25 year lifetime we have 5000 divided by 4380 is 1.141 where 4380 is the operating hours per year. 25 divided by 1.141 gives us 21.91 replacements per lifetime.

$CC = CC_{fc} \times (1 + 21.91 \times 0.3)$

CRF = the capital recovery factor which is again $\frac{i(1+i)^t}{((1+i)^t-1)}$ with i = 0.08, the discount rate, and t = 25, the lifetime of the electrolyzer.

$F_{o\&m}$ = the fixed operation and maintenance cost, which we found to be 5% of the capital cost.

The final term represents the cost of the hydrogen used in the fuel cell. It uses the cost of hydrogen calculated for the electrolyzer. But because the 100 MW refers to the power output of the fuel cell, and not the hydrogen chemical energy consumed, the cost used in the FCA must be corrected by the efficiency (chemical energy to electrical energy) of the fuel cell.

Finally the levelized cost of energy for the fuel cell can be expressed as Fuel Cell Levelized Cost of Energy $(LCOE) = \frac{AnnualizedCostFC}{100MW \times 8760h \times CF}$

6 Results

We ran multiple sensitivity analyses to see what the limiting factors were. Using our equations for the levelized cost of energy, we varied the cost of electricity, the capital cost of the electrolyzer, the efficiency of the electrolyzer, the capital cost of the fuel cell, and the efficiency of the fuel cell. We entered the equations into an Excel document and varied each of these parameters individually while holding the others constant. This gave us tables of data that we used to track the impact of a single variable on the levelized cost. We graphed the variable against the levelized cost of the fuel cell so we could identify any trends. The graphs showed us which variable resulted in the largest range of costs, which indicated that it had the biggest impact. We identified these as the limiting factors.

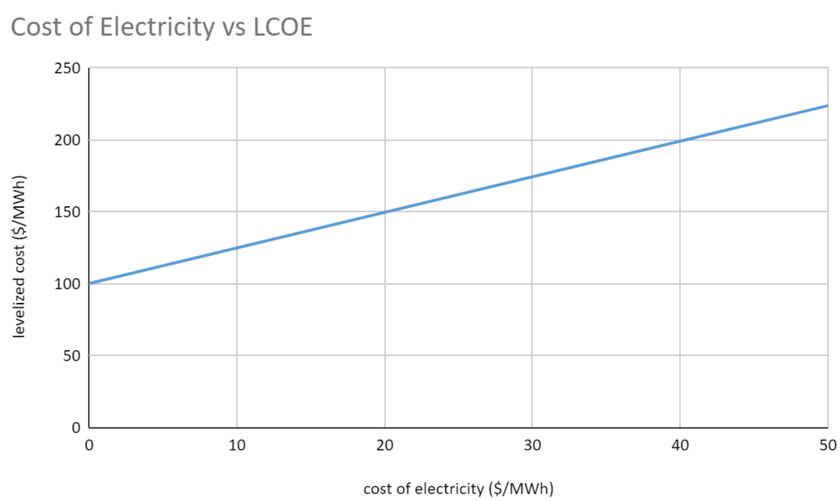

Figure 1: Cost of Electricity vs LCOE. The cost of electricity has a large impact on the levelized cost of energy. When the cost of electricity is free, the levelized cost is low, \$100/MWh, but increasing the cost of electricity to \$50/MWh increases the levelized cost about \$125. The electricity graphed above is used to power the electrolyzer and would be produced by renewables such as solar and

wind.

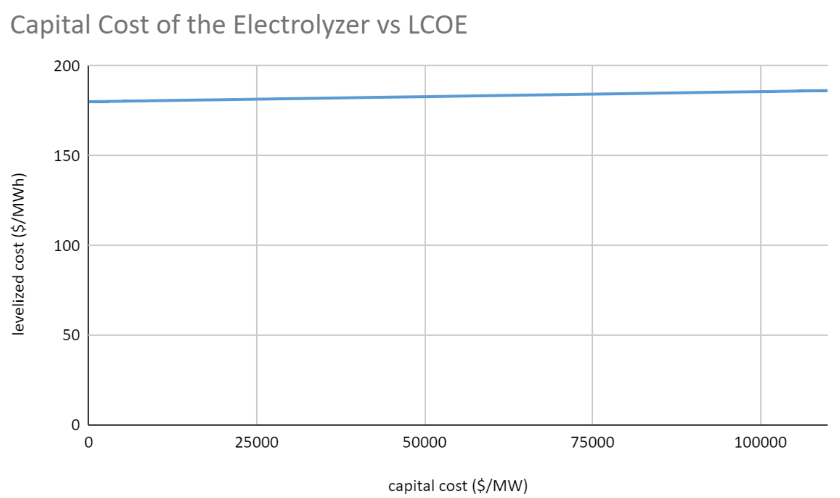

Figure 2: Capital cost of the electrolyzer vs LCOE. The capital cost of the electrolyzer had a very small impact on the levelized cost. Increasing the capital cost of the electrolyzer by $75000 resulted in the levelized cost remaining at around $175 per MWh. We concluded that this was not a limiting factor and when trying to reach the goal of $50/MWh, we decided to alter this value.

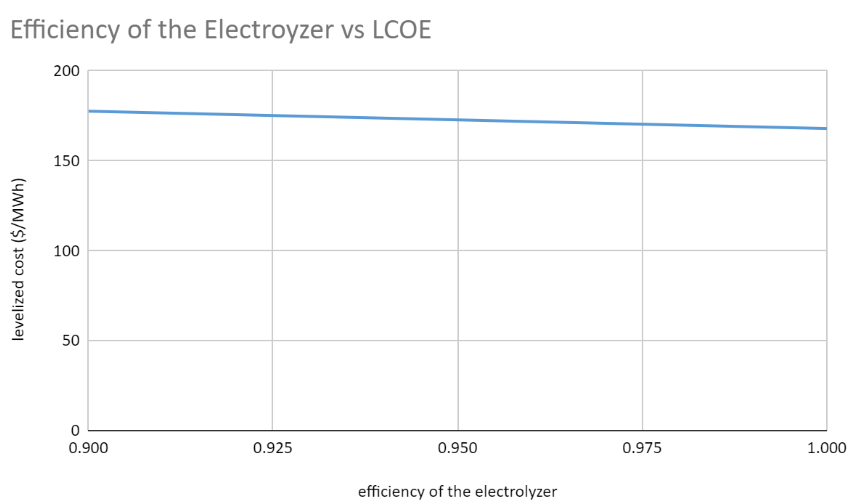

Figure 3: Efficiency of the electrolyzer vs LCOE. The efficiency also had very little impact on the levelized cost.

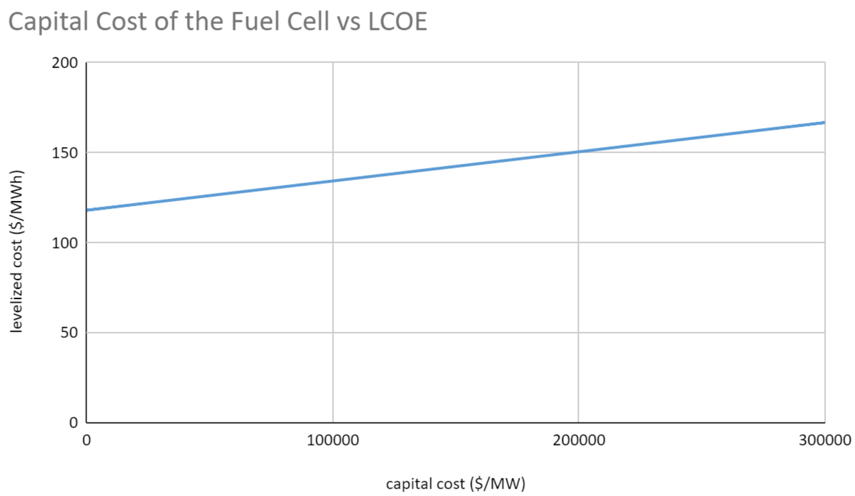

Figure 4: Capital Cost of the fuel cell vs LCOE. The capital cost of the fuel cell had a more drastic impact on the levelized cost and we identified it as a limiting factor. Because of this we decided to alter it more drastically later when we were trying to reach the practical price of $50/MWh.

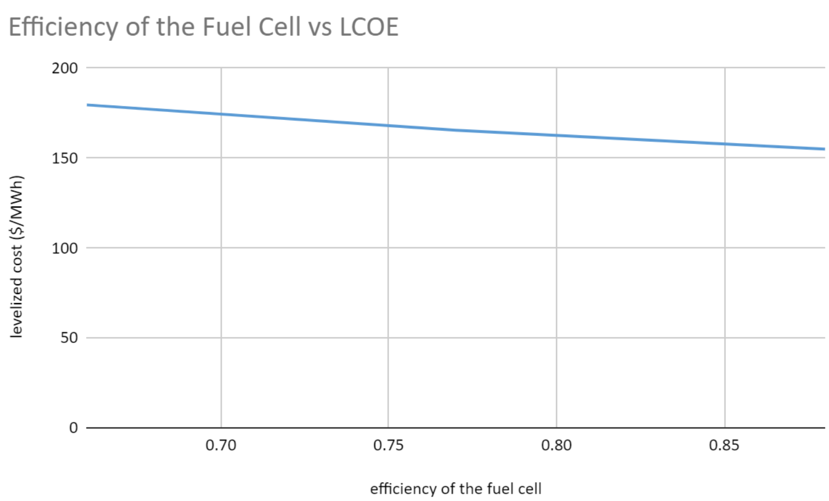

Figure 5: Efficiency of the electrolyzer vs LCOE. Although there is a visible decrease in levelized cost as the efficiency of the fuel cell increased, it was not significant in comparison to the other slopes we saw in our research. Increasing

efficiency dramatically did not yield a large decrease in levelized cost.

7 Discussion

From Figure 1 and Figure 4, we deduced that the cost of electricity and the capital cost of the fuel cell had the biggest impact on the levelized cost of energy. However, we found that the cost of hydrogen per megawatt hour was around $100-$225. Unfortunately the competitive price of hydrogen per megawatt hour is $50, as this is the levelized cost of energy for the existing natural gas system. We ran additional sensitivity analyses, altering these limiting variables and discovered that one way to reach the competitive cost of $50/MWh was to set the cost of electricity to $0 and cut the capital cost of the fuel cell in half. Practically speaking, this could mean using curtailed energy which is essentially excess energy, like in the Li study. Some examples of times energy would be curtailed is if renewable sources are located far from the grid and transporting the energy would be cost inefficient. In these cases, the cost of electricity could even be negative. Government subsidies could help lower the capital cost of the fuel cell. Economy of scale could also be applied here, where the more prevalent this technology is on the market, the more the cost is driven down.

8 Conclusions and Further Research

Time is running out to make systematic changes in the energy sector to prevent permanent climate damage. To make these large-scale changes, there needs to be a system that can replace the current one. An electrolyzer-fuel cell system could replace natural gas plants. We discovered through our sensitivity analyses, that this is an economically feasible solution. One way for the electrolyzer-fuel cell system to be directly competitive with the cost of natural gas would be if the renewable energy used to run the plant was free and subsidies cut the capital cost of the fuel cell in half [4].

In our equations, we did not account for the costs of storage, pressurization of the gas, and transportation among other things. Our cost is the bare minimum, whereas in the future we would do a more complete investigation. We approached it from an engineering standpoint, in that we looked at investment costs, not just the variable costs. From an economic standpoint, the variable costs are the costs that would need to be focused on and altered to make the system more competitive. In the future, this model could be used to see the effect on the levelized cost of energy when more than one variable is varied. This could provide us with the lowest possible cost, not just the competitive cost. At the end of our research, we verified that thermal plants had similar numbers to the electrolyzer-fuel cell pairing and that our work could be applied to a thermal plant-fuel pairing too. This would allow us to explore different options for lowering the levelized cost of energy.

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