# Feasibility Study of a Solar Photovoltaic to Hydrogen Electrolyzer System at the Richmond Field Station

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## ABSTRACT

With the transportation sector having a substantial impact on global $CO_2$ release, hydrogen fuel cell vehicles provide consumers with a strategy to reduce transportation-related carbon emissions Hydrogen for fuel cell vehicles is largely produced through an energy intensive process known as steam reformation of natural gas. Recently, there has been research and development into the use of solar photovoltaic (PV) energy to power electrolyzers to generate hydrogen with a much lower carbon footprint. These electrolyzers are modular and can be scaled to many sizes and for many sites. Through online data collection and solar access surveys, I explored the appropriate sizing and output levels of a solar to hydrogen system at UC Berkeley's Richmond Field Station to meet its fueling station's needs. I explored three different hydrogen generation scenarios: 1) an electrolyzer powered by just a solar array 2) an electrolyzer powered by solely grid energy and 3) an electrolyzer powered by a combination of the two energy sources. I found that all three scenarios of generating hydrogen onsite will save money over a period of 20 years compared to the station's current system of purchasing conventionally generated hydrogen from a local refinery. Each scenario also adds its own carbon footprint to the station. While the method of producing hydrogen fuel at the lowest initial cost entails using grid energy as the sole power source of the electrolyzer, this system also emits much more $CO_2$ than relying exclusively on a PV array for electrical inputs. Onsite hydrogen generation presents a unique opportunity for hydrogen infrastructure to spread throughout the country and further encourage and provide opportunities for commuters to switch to fuel cell vehicles.

## KEYWORDS

Proton exchange membrane, solar-grid power combination, GIS, lifecycle analysis, sustainable transportation

## INTRODUCTION

Most hydrogen generated for fuel cells is made through a process known as steam reforming of natural gas. This steam reformation process is very energy intensive. Superheated steam is used to separate pure hydrogen molecules from the natural gas (Oertel et al. 1987). The process not only needs steam, which requires energy to make, but also natural gas in its pure form (Lukyanov et al. 2009). This is the most cost-effective way to directly produce hydrogen (Blok et al. 1995). However, because natural gas is an exhaustible natural resource and the process produces $CO_2$, researchers have been looking into other methods of producing hydrogen.

Generating hydrogen using renewable energy sources is an alternative to the conventional steam reformation process. The hydrogen fuel is made by using solar energy from PV cells to electrolyze water (Gibson & Kelly 2008), which only uses the electricity from the solar cells and water; no fossil fuels are (directly) needed and no $CO_2$ is released. This system, known as proton exchange membrane (PEM) electrolysis, can achieve a hydrogen generation efficiency of up to 12% (Gibson & Kelly 2008). Some benefits of using a PV to PEM electrolysis process include: 1) its compactness, 2) its small environmental footprint, 3) its ability to produce hydrogen on site and on demand, 4) its ability to be used at homes and small-scale service stations, and 5) its modularity, allowing tailoring to the requirements of specific sites (Clarke et al. 2009). These benefits apply mostly to small-scale projects and fueling stations.

An example of a small hydrogen fueling station that is looking to adopt this production system is the Richmond Field Station (RFS). Currently, their fueling station runs on hydrogen from a refinery in Richmond, CA, which uses the conventional steam reformation process. From there the hydrogen is transported to the fueling station via trucks. The RFS's refueling station typically distributes no more than around 13 kg of hydrogen per day. Accordingly, a prospective PV-to-hydrogen apparatus at the field station would need to produce just enough fuel to provide for the station's daily use. This could effectively cut the station's reliance on imported hydrogen fuel. While producing hydrogen on site would provide many benefits for the RFS, it is unknown how the economic and environmental consequences of this project would compare to the current hydrogen-provisioning regime.

## Research objectives

My central research question was: Relative to its current means of acquiring hydrogen, what were the economic and environmental costs and benefits of installing a solar PV to PEM electrolyzer at the Richmond Field Station? I informed my work by answered two related, subordinate questions: 1) Where was the best location to install the solar PV array to maximize energy production? 2) How much of the electricity needed to power the PEM electrolyzer should come from the solar PV cells verses the grid? During the life of the project, I used various tools and techniques to collect my data and address my questions. Foremost, I needed to find the optimal location for the PV array. To do this I used the amount of sunlight per year that my study site receives in the form of solar access plus coordinates to geo-reference my data. Solar access is the insolation available accounting for shade divided by the total insolation available without shade and is expressed as a percent. Solar access of 100% implies that there are no shading obstructions within the field of view of the surface. I also used solar radiation data in the form of $kWh/m^2/day$. Next, I found economic data estimating the cost of implementing the PV-PEM electrolyzer on my study site and the savings of reducing dependency on purchased hydrogen. This included pricing for various types of solar panels and PEM electrolyzers. Finally I found GHG emission data of the steam reformation process and grid energy use, mostly in the form of kg $CO_2$ / kg $H_2$ and kg $CO_2$ / kWh respectively.

# METHODS

## Study site

The Richmond Field Station (RFS) is an off-site academic facility used mainly for large engineering research projects. Located on the San Francisco Bay six miles northwest of the central campus of University of California, Berkeley, this 152-acre property has been owned by the university since the 1950s. The station is comprised mostly of empty fields and scattered buildings and parking lots. The Richmond Field Station is the current home of the Transportation Sustainability Research Center (TSRC). The TSRC was formed to study the economic, social, environmental, and technological aspects of sustainable transportation. They also are in charge of operating and maintaining the hydrogen fueling station that is situated next to their headquarters. This fueling station distributes hydrogen gas to power fuel cell vehicles. As of now, the hydrogen comes from a large-scale production facility in the Richmond area.

**Data collection**

To determine the potential solar energy resource, I measured site shading and solar irradiance. The Solmetric Suneye tool gives the user the solar access percentage of available sunlight throughout the year or the amount of incoming sunlight that will strike the ground unimpeded by objects like trees or buildings. Solar access of 100% implies that there are no shading obstructions within the field of view of the surface. I disaggregated the annual sunlight data into two seasonal periods: October – April (Winter) and May – September (Summer). I used a GPS to georeference my sampling points and chose my study area to be the field closest to the refueling station. Using the GPS and Solmetric Suneye, I took 24 samples along my study site in a uniform pattern with a 5 meter spacing. To get the solar irradiance level, I used a GIS database showing average solar irradiation in the Richmond area. I then used the following calculation to determine solar radiation on my study site:

$$\text{Annual Solar Access (\%)} * 5\ kWh/m^2/\ day * 365\ days/year$$

To calculate the total amount of hydrogen produced using the energy provided from the solar PV panels, I gathered sizing information of the solar PV panels and the hydrogen electrolyzer production rates from various websites and scholarly articles.

Using RFS spending records on conventionally generated hydrogen, I gathered financial information regarding the current and prospective hydrogen provisioning systems to find the cost savings of reducing dependency on conventionally generated hydrogen. To collect data about the components of a PV-to-H2 system, I found cost information on system pricing from various solar and electrolyzer companies on various solar panel and hydrogen electrolyzer models.

To find the greenhouse gas emissions reduction potential of the proposed system, I collected carbon emission data. The emissions associated with the current system were estimated by considering both the H2-generation process and the transportation of that H2 to the RFS. I calculated the direct and embedded CO2 emissions associated with the current hydrogen-provisioning scheme using a previously conducted life cycle analysis (LCA) of the steam reformation process (Spath & Mann 2000). I also found the carbon released by the trucks transporting the hydrogen from the hydrogen production facility to the Richmond Field Station. This data was in the form of total mileage driven and average truck mpg.

**Data analysis**

I integrated the previously collected solar data and GPS coordinates into a GIS database to find the area with the greatest amount of yearly sunlight and solar radiation. This allowed me to find the optimal location to install a solar array. I also used this solar access data as a percentage variable to calculate the maximum hydrogen production.

I used the solar irradiance levels I collected paired with the efficiency rates of the solar panels and the sizing of the hydrogen electrolyzer to find the total amount of hydrogen that the system can produce. The electrolyzer chosen needed to be the optimal size as to supply the fueling station with it's daily output but not too large as to produce unused hydrogen and have excess costs.

After gathering information from various electrolyzer websites I found the optimal electrolyzer to meet the station's needs. I also was able to find the amount of energy it requires to run at full capacity. From there I was able to fin how much solar power would be needed to run the electrolyzer at full capacity. The equation I used was:

*kWh/day / 25% solar capacity factor / 24 h/day = kW of installed solar*

I then needed to conduct an economic valuation to see which hydrogen generation scenario was cheapest over time. I compared the prices over a period of 20 years. First, I found the initial cost of the electrolyzer, which ended up being $214,847. I then estimated cost of solar panels based on the size of the array. Using the base case of 100 kW of solar costing $154,560, I estimated the price of other solar arrays of varying sizes using this formula:

*100 kW / $154,560 = Size of array / Price of array*

I calculated the discounted present value of operating an electrolyzer versus purchasing hydrogen. The formula I used was $NPV = C / (1+r)^t$ where C is the cost of the electrolyzer, r is the discount rate, and t is the number of years the model is run for.

To find the cost of grid energy I used a number of techniques. After drawing on some data acquired from PG&E's website, I found two prices for power. One of the prices was off-peak and the other was on peak. Off-peak power was cheaper and applied to power that was being used during night and early morning when people are not generally consuming energy. I was able to plug in different energy costs to reflect a range of pricing based on the time of day and power consumption needs of the electrolyzer.

Because the environmental calculations were not temporally relevant, I just needed to subtract the carbon emitted from the conventional hydrogen generation process from the carbon emitted using the PEM electrolyzer to determine the net carbon saved. The steam reformation LCA study provided the amount of $CO_2$ released during the steam reformation process, while I calculated the $H_2$-transportation emissions by multiplying truck travel distance by vehicle efficiency and the carbon intensity of diesel.

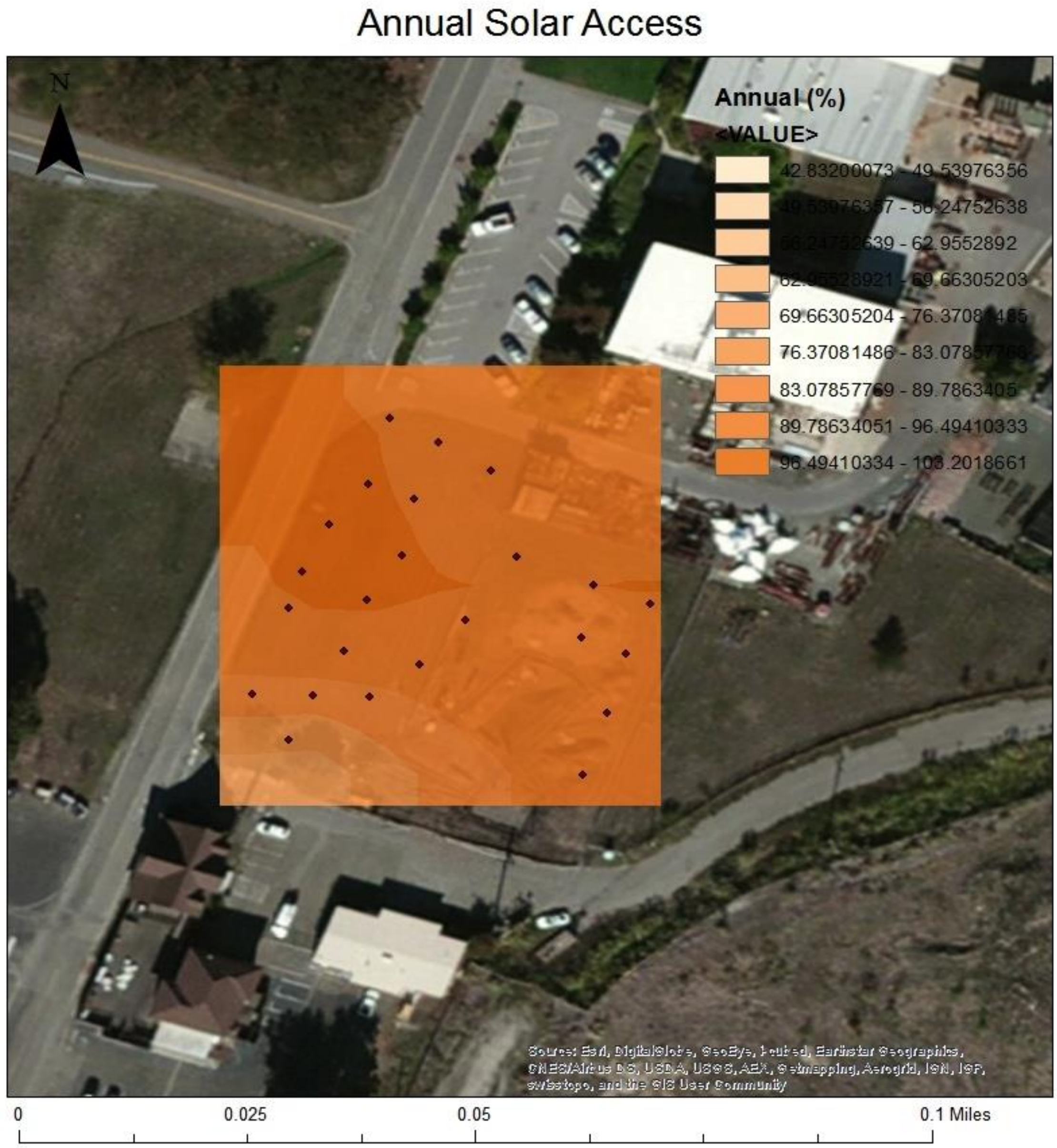
Each hydrogen production scenario generated different levels of carbon. For an electrolyzer powered by just solar panels, all you have to factor in are the embedded emissions of the electrolyzer and the PV array (Fthenakis & Kim 2006). This includes the life cycle of the solar array and the electrolyzer, along with emissions associated with installation and maintenance For a scenario where the gird is being used to power the electrolyzer, I needed to find the average grid emissions for the local energy provider.

## RESULTS

### Solar resource

The first map I made shows annual solar access over my study site (Figure 1). The darker orange represents more annual solar access. The winter months generally receive less solar insolation and have a lower solar access percent than do the summer months. I found that daily solar radiation value of the city of Richmond amounts to 5 kWh. I assumed that my study site receives the same amount of insolation because it is located in Richmond.

**Figure 1. Annual Solar Access.** Determined using georeferenced solar access points and the spline method of interpolation. Sample points are expressed as brown dots. The values range from a yearly solar access of 56% to 98%.




The next map shows the distribution of potential energy production from solar panels across my study site (Figure 2). My study site with 24,000 square feet has sufficient space for a solar PV array large enough to power the electrolyzer by itself. The 163 kW solar system will take up approximately 12,500 square feet. The grid assisted solar power system modeled for this project uses a 100 kW solar system with the remaining 63 kW powered by the grid. This would require 7,700 square feet of space for the solar array.

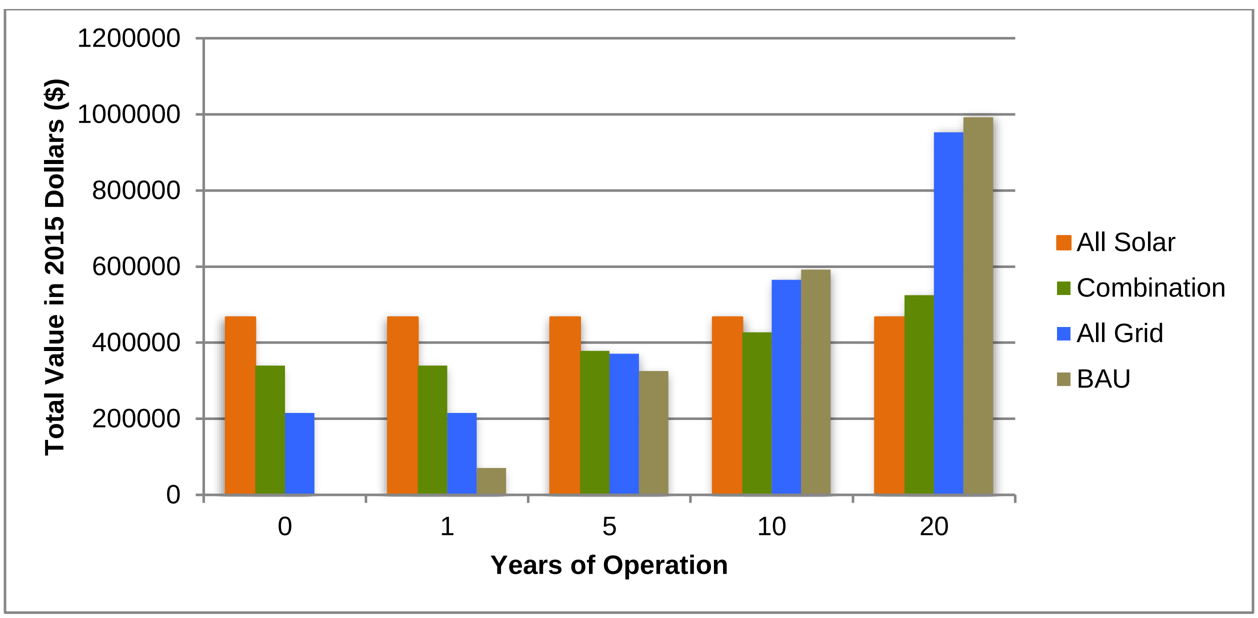
**Figure 2. Annual Solar Energy Map.** Raster map showing range of solar irradiance levels that the study site receives. Ranges from 1311 to 1778 kWh/m$^2$/year

The company ProtonOnsite makes PEM electrolyzers that vary in sizing and output levels. The optimal electrolyzer for the Richmond Field Station would be their H6 model. The H6 PEM electrolyzer running at full capacity will be able to produce 13 kg of hydrogen per day, effectively generating the 10 kg of hydrogen that the station distributes daily. The H6 electrolyzer needs 980 kWh per day to run at full capacity and generate all 13 kilograms of hydrogen.

The H6 unit costs $214,847. I compared the amortized price of the PEM electrolyzer with the recurring costs of purchasing hydrogen from the steam reformation producer. I also had to account for using grid power and solar power.

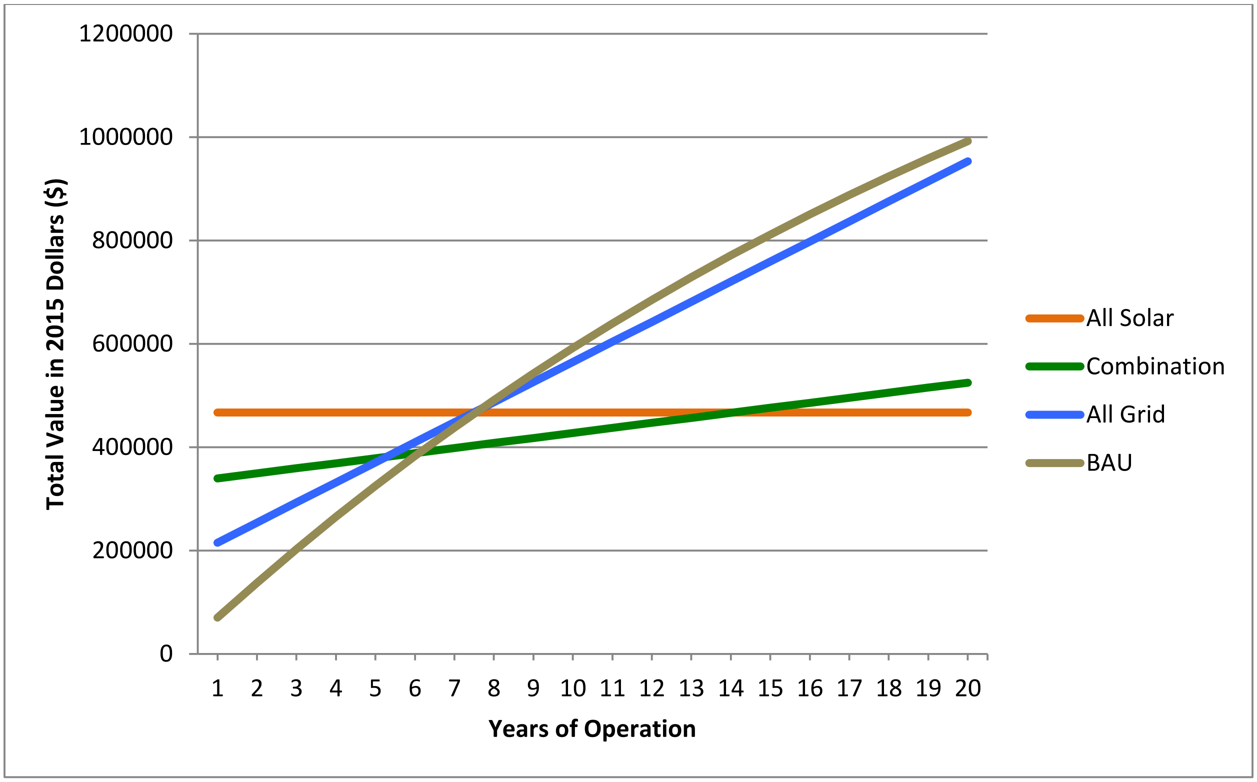
A solar array large enough to power the electrolyzer at full capacity (163 kW) costs roughly $252,000. Cost of power from the grid is roughly $0.07/kWh during off-peak times and $0.147/kWh during peak hours. Under the grid-assisted solar scenario, power would be supplied to the electrolyzer at off-peak times, making the recurring costs of electricity significantly lower than the all grid scenario (Table 1).

**Table 1. Discounted (4%) Financial Analysis of Various Electrolyzer Powering Scenarios.** This chart shows the discounted cost of each hydrogen generation scenario along with purchasing hydrogen from local refinery (BAU) over a period of 20 years at a rate of 4%. There are four scenarios, three of which involve generating hydrogen using a PEM electrolyzer. The three hydrogen generation scenarios each use a different source of electricity to power the electrolyzer. The first scenario is an all-solar scenario where the PEM electrolyzer is simply powered by a solar array. The next one is a combination scenario where both grid and solar energy are used to power the electrolyzer. The last of the three hydrogen generation scenarios is an all grid scenario where the electrolyzer will be powered by just grid energy. The last scenario is business as usual. This means that the Richmond Field Station's refueling station will continue to purchase hydrogen from a local refinery.



The next figure shows the discounted price of each scenario as a line chart. Here you can clearly see where each scenario surpasses the other as a more cost effective option. There is a point at around year 8 where the costs for the all grid scenario, the all-solar scenario, and the business as usual converge, only to have the all-solar scenario stay flat and the other two continue upwards (Figure 3).

**Figure 3. Discounted (4%) Financial Analysis of Various Electrolyzer Powering Scenarios.** This graph shows the discounted price of each scenario represented as a line. The same four scenarios apply as above.




## Carbon implications

Through a LCA, I found that the steam reforming process emits on average 12 kg $CO_2$ per kg $H_2$ produced (Spath 2000). The hydrogen is purchased and transported from the Chevron refinery in Richmond, making the transportation emissions small but non-negligible (11.8 kg $CO_2$ round-trip). These trucks transport up to 49,000 liters, however, I am assuming a liquid hydrogen trailer size of 30,000 liters (2,123 kg). This makes the transportation carbon emissions for hydrogen 0.006 kg $CO_2$ per kg $H_2$. In sum, the lifecycle GHG emissions for purchased hydrogen are mainly from the $H_2$ generation process. The bulk of emissions associated with the proposed PV-PEM system are embedded emissions due to the production and installation of the system. I found the embedded emissions of a solely grid powered PEM electrolyzer to be 1.5 kg $CO_2$ per kg $H_2$ generated. Using grid power also changes the project's environmental footprint. The $CO_2$ emissions of using solely grid power to run the PEM electrolyzer are 13.3 kg $CO_2$ per kg $H_2$ generated, and the combination scenario where 100 kW of solar are installed emits 6.1 kg $CO_2$ per kg $H_2$. Each method of hydrogen generation emits a distinct amount of $CO_2$.

## DISCUSSION

Climate change is the most global environmental issue that we are faced with (NASA 2015, AAAS 2006, US National Academy of Sciences 2005). Many changes have been made in our society, economy, and environment to decrease or regulate the levels of greenhouse gases we emit and alleviate the threat of climate change. Personal transportation emissions make up a significant portion (27%) of the United State's greenhouse gas emissions and therefore contribute greatly to climate change (World Resources Institute 2008). Hydrogen fuel cells are an example of a technology that can eliminate greenhouse gas emissions from the transportation sector. However, the lack of hydrogen-based infrastructure has impeded this technology's ability to spread and flourish (Lipman 2011, Lipman et al. 2004). I conducted a study to find out the benefits and drawbacks to installing a hydrogen electrolyzer to produce hydrogen locally relative to off-site H2 production.

First, my hydrogen output results confirmed that a PEM electrolyzer will be able to supply the RFS with enough hydrogen to satisfy all its needs. Second, the financial analysis indicated that [installing a PEM electrolyzer will be cheaper in the long run (10 years) than continuing to purchase hydrogen from the local refinery]. Lastly, the greenhouse gas model shows that using a PEM electrolyzer will save [kg of $CO_2$] if run off of grid power and [kg of $CO_2$] if run off a combination of solar and grid energy. This system has proven to be versatile, adapting to the user's needs (Barbir, 2005), making it a viable means of spreading hydrogen fuel across the state, country, and even globe.

**Hydrogen Output**

The PEM electrolyzer is able to supply the fueling station with enough hydrogen to meet its daily distribution demand, meaning that ties to purchased steam reformation hydrogen can be cut and the Richmond Field Station can generate its own hydrogen on site. However, if the RFS does not wish to produce all of their hydrogen locally and would rather maintain a base amount that will be purchased and shipped in, purchasing a smaller electrolyzer system that produces less hydrogen and consumes less energy would be preferable to the system discussed here, as the small system would be used to a higher capacity and therefore would have lower capital and levelized costs.

Grid-assisted PV energy is also a feasible alternative, which requires a smaller solar installation. Despite it not having the lowest carbon footprint, it does prove the station with a level of reliability that a pure solar scenario would lack. One of the major issues with solar power is its unpredictable nature. With a steady source of electricity provided by the grid, hydrogen can be made even when the solar panels are not in use.

**Economic Model**

My economic model shows that at year 20, it is cheaper to produce hydrogen on site than it is to purchase it from a refinery. The Richmond Field Station should consider their desired time frame of the project when deciding which system to implement. The RFS also should consider their willingness to pay upfront because each scenario has a significantly different initial cost. The discount rate also has a significant effect on the results. As the discount rate approaches 13% the net present costs of purchasing steam reformed hydrogen becomes as attractive as the combination solar and grid scenario. At 15% the business as usual scenario costs just as much at year 20 as does the all-solar scenario. Whichever discount rate is chosen will have an impact on the final results.

**Environmental Model**

Using a PEM electrolyzer powered solely by PV energy emits only 1.5 kg of $CO_2$ per kg $H_2$ generated, making it the cleanest hydrogen generation scenario. Interestingly, the all grid scenario was the one with the greatest carbon footprint, even more so than the steam reformation process. Clearly, the more grid power used, the more $CO_2$ is released.

**Limitations and Future Directions**

The analysis I performed shows the daily financial cost of the scenarios that I chose as well as their respective greenhouse gas emissions. This model can be adapted to fit a range of application scales through using different sized electrolyzers, different renewable energy/grid power combination ratios, and different discount rates. Greenhouse gas emissions should remain fairly constant, especially for areas that power their grid using the same electricity mix. Because the model can simulate financial and environmental costs of using grid power to run the PEM electrolyzer, it can be applied virtually anywhere that receives grid power.

My model's limitations come from the solar access, hydrogen production, and greenhouse gas data. Real solar access values will deviate from the modeled quantities due to anomalies like cloud cover, dirty solar panels, or changes in RFS infrastructure that may occur for the 20-year lifetime of the equipment. I did not factor in unexpected losses of hydrogen into my hydrogen production model, as it would be very difficult to simulate randomness. Lastly, the lifecycle analyses of greenhouse gas emissions associated with the steam reformation process and the PEM electrolyzer installation project did not consider several embedded or indirect emissions sources. An incomplete LCA would likely underestimate the carbon emission values for steam reformation. For example, emissions associated with fabrication and shipment of the electrolyzer and solar panels were not included, along with detailed natural gas extraction emissions information.

The next steps following this study are two fold: 1) to test the model on other sites in California and 2) to install and operate one of the scenarios at the Richmond Field Station. This study has proved that electrolyzer systems are modular and can be powered by any source of electricity. It would be interesting to see what the model can say about installing a similar system in other areas of the state. The separate study might also give different results that would be interesting to compare to those found in this study. Using different economic and environmental data from other electricity providers as well as differing solar availability would make for another project and could further prove the system's scalability.

Actually installing the system at the RFS would provide real results that can be compared to my model. This would directly determine how successful my model is in determining hydrogen output, electricity input, financial costs, and greenhouse gas emissions.

**Broader Implications**

The most pressing issue limiting the use of hydrogen-fueled personal transportation is low access and nonexistent infrastructure (Lipman et al. 2004). People are hesitant to switch to a hydrogen vehicle mostly because of the lack of hydrogen infrastructure. PEM electrolyzers and on-site hydrogen have an exciting future because they directly solve this issue.

PEM electrolyzers even have the ability to be implemented in harsh, remote climates (Chade et al. 2015) and can be powered by many differed energy sources (Barbir, 2005), making it adaptable for use all around the world. The system that I have modeled is a modular and scalable way to produce hydrogen on site. If paired with a fueling station, the locally generated hydrogen can be directly distributed to customers through the refueling station. The PEM electrolyzers in my study can run on any source of electricity, and therefore, can be implemented in all areas that are located on the grid or receive some source of renewable energy. Similar studies have been conducted and found that other sources of renewable power are able to power a PEM electrolyzer (Absi et al. 2015, Feroldi 2015).

The transportation sector generates a substantial mass of greenhouse gases in the United States (World Resources Institute 2008)**.** Hydrogen fuel cell vehicles are a viable alternative to conventional combustion engine cars. Fuel cell cars have the ability to make a substantial contribution to climate change mitigation because their only tailpipe emission is water vapor, with the majority of emissions occurring during the hydrogen production process (Lipman 2011). Using sustainable hydrogen generation practices, we can eliminate these upstream hydrogen generation emissions and further develop the deficient hydrogen infrastructure by creating scalable hydrogen production systems. This could effectively reduce the barrier to owning a hydrogen fuel cell vehicle, leading to their wider adoption and use and avoiding the release of massive amounts of greenhouse gas from the transportation sector.

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## APPENDIX A

**Figure A1: Seasonal Solar Access Comparison.** Average solar access is higher in summer months (May-Oct) than in winter months (Nov-Apr). The solar access for both time periods were factored in to create the annual solar access map.

May-Oct Solar Access