Cornell University

School of Civil and Environmental Engineering

Sustainable Hydrogen

From Renewable Source to Energy Center to Transportation Applications

Peter Wise, Nidhi Maniar, Qizhou Guo, Yuxiang Liu, Mingzhe Li, Huiya Yan

Fall 2021

Acknowledgement

We would like to extend our most sincere thanks to the following for making our project successful by providing us with information, physical and moral support, and a conducive atmosphere throughout the year. Every minute of your time spent contributing to our success will always be highly appreciated.

All of the School of Civil and Environmental Engineering faculty and office staff for helping us to enroll in this course and support throughout the entire course duration.

We would like to extend our thanks to Mr. David Lubin, the lead developer of the proposed ChainWorks project. It was indeed a great experience visiting the 100 years old site and evaluating the potential of hydrogen storage at ChainWorks. We would also like to thank the PV-H2 microgrid Stakeholders from the Ithaca Community Power organization for their continuous knowledge sharing and feedback sessions.

Finally, our advisor, Professor Francis Vanek, for your great leadership, continuous guidance, encouragement, and constructive reviews. The late hours and tireless efforts you put in to ensure our success will always be cherished. We're grateful to have been given the opportunity to work on this project and contribute to Ithaca's sustainability goals.

Executive Summary

As energy needs grow in our current age, so does the need to develop sustainable sources of energy increase. Hydrogen technology has gained increasing attention in the energy industry for its potential role to play in the energy transition and the decarbonization of our energy system. In this project, we investigated the incorporation of hydrogen technology into the Ithaca energy portfolio. The ChainWorks facility on South Hill in Ithaca has existing unutilized building space that has potential to function as a central hub for the project. Incorporating hydrogen technology in Ithaca would support Ithaca's net-zero carbon goals and advance the adoption of alternative transportation options in the area. More importantly, this investigative project serves as a learning opportunity to inform industry and further development and adoption of hydrogen energy systems.

Solar and wind energy were investigated to provide the power supply for hydrogen production. A rough balance of solar and wind production was selected to seasonally complement each other. A single 1.7 MW wind turbine and total of 4 MW of solar capacity were selected to be installed with annual productions of 5.51 and 4.98 GWh, respectively. This total of 10.0 GWh of energy per year powers a 1.25 MW proton-exchange electrolyzer, which produces 533 kg of hydrogen per day. This supply of hydrogen was found to be capable of supporting 98% of the TCAT bus fleet's energy demands, 1160 Toyota Mirai FCEVs, or 3.70 GWh of electricity produced back to the grid via fuel cell technology. A fueling station is proposed to be installed at the ChainWorks facility to supply buses and FCEVs with hydrogen. Because of the challenges of long-term high-pressure storage—namely leakage and high capital cost of tanks, a small 105 kg capacity from a set of 4 tanks at 70 MPa will serve as storage at the refueling station.

The economics of this project are not fully explored due to the rapidly changing characteristic of the hydrogen market in its late infancy stages. As hydrogen technology develops and becomes more widely implemented, there is potential for hydrogen production to be centrally located in areas of high renewable energy production. Storage remains a critical component of a hydrogen production system as it allows electrolyzers to time their production when costs are lowest and bank a supply of hydrogen to hold over through times of high pricing. In this way, hydrogen production will be using the lowest cost electricity available on the grid, allowing for greater accommodation of intermittent production of renewable energy as hydrogen production from electrolyzers could be dispatched when electricity cost is low.

Developing hydrogen systems with sufficient storage will be a key area in creating hydrogen systems capable of achieving low-cost production and supporting renewable energy development. The investigation in this project shows that in initial stages of hydrogen technology incorporation, distributed production of hydrogen on-site will be the most physically and economically feasible way to incorporate hydrogen production into energy systems in the near-term.

Perhaps the most important considerations of this project that should not go undervalued are the learnings, insights, and community exposure to hydrogen technology. In addition to technological barriers, people will have to need reasons and trust to adopt hydrogen technology. Exposure to hydrogen systems with good reliability and economic performance will be needed in promoting adoption of hydrogen technology to expedite the energy transition.

List of Authors

Sustainable Hydrogen team:

1. **Huiya Yan** (M.Eng. in Transportation Systems Engineering)

   She completed her undergraduate major is Traffic Engineering from Beijing University of Technology. Huiya's existing knowledge has a lot to do with transportation planning and management, such as network optimization and traffic impact analysis. She interned at the Energy Transition Department of Beijing Transport Institute wherein she learned about charging stations and the development of new energy vehicles in China.

2. **Mingzhe Li** (M.Eng. in Transportation Systems Engineering)

   He completed his undergraduate degree in Civil Engineering from the University of Tennessee at Chattanooga. He had an internship at a transportation construction company for six months. In this project, he plans to contribute to research on solar and wind energy acquisition calculation and the energy efficiency, etc. He possesses good knowledge in the process of analyzing the general transportation of hydrogen.

3. **Nidhi Nitin Maniar** (M.Eng. Chemical Engineering student)

   She completed her undergraduate degree in Chemical Engineering from University of Mumbai. After her undergrad, she worked in the Oil & Gas Industry for about 2-years as a Process engineer. Here at Cornell, she is working on enhancing the efficiency of Li-ion batteries, Six sigma Process improvement project, and other consulting projects. Her knowledge in Energy storage solutions coupled with Python & MATLAB would help bring an all-round perspective to this project. She also works as a student associate for a Solar Company in the US.

4. **Peter Wise** (M.Eng. in Environmental Engineering)

   Peter holds a B.A. in Physics with a strong interdisciplinary and economics background. Peter's interests lie in renewable and alternative energy production/saving systems. He has had some exposure in the past to market analysis and feasibility of residential scale solar, wind, and geothermal energy systems. Peter's knowledge and experience pertains best to the energy generation side of the project—the analysis and feasibility of the production of hydrogen from renewable sources.

5. **Qizhou Guo** (M.Eng. in Environmental and Water Resources Engineering)

   He finished his undergraduate program in Civil engineering. He can estimate the cost for these infrastructures like refueling stations or pipelines. He interned at geotechnical test center and a construction company. His current courses mainly focus on modeling like probabilistic models and data analysis by using Fourier transform. He holds good knowledge in MATLAB and Python.

6. **Yuxiang Liu** (M.Eng. in Civil Environment Engineering)

   Yuxiang holds a B.S. in Ecosystem and Sustainable Development from Colorado State University. Yuxiang now focuses on the relationship between energy sources and the sustainability of the ecosystem. Besides, he also examines the impact of new technology on environmental quality. Yuxiang is working on hydrogen fuel cells and its type in this project. He is excited to look into the potential applications of the fuel cell.

Advisor: Prof. Francis M. Vanek (Senior Lecturer, Civil and Environmental Engineering)

List of Tables:

List of Figures:

Table of Contents

1. Introduction

1.1. Motivation

Why is the energy demand increasing?

Energy demand is growing across the globe and is forecasted to increase in the next several decades (US EIA, 2019). The challenge exists in meeting these demands while balancing energy production's social and environmental impacts. In addition, growing populations and increasing living standards in developing countries will place even more order on energy resources. The graph below shows how energy demand is going to increase in the non-OECD countries:

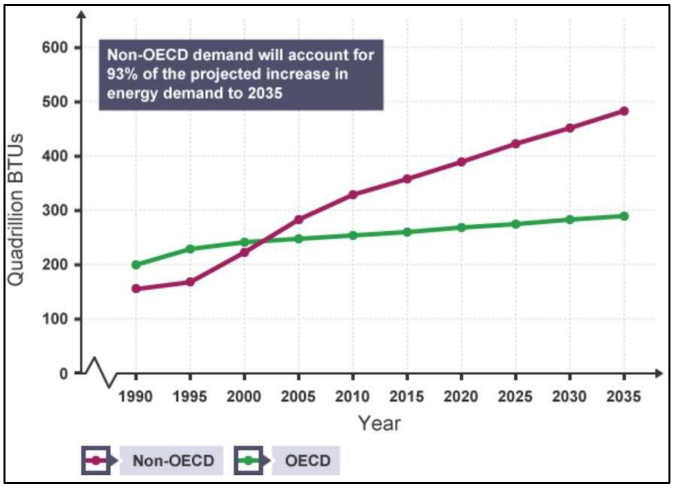


Figure 1.1.a: Increasing energy demand in OECD and non-OECD countries.

Our current economy is dependent on cheap energy, primarily generated from fossil fuels (US EIA, 2021). However, as our current energy usage significantly impacts the climate, exhausts resources, and causes injustices and inequities, we look to alternative sources to meet energy needs more sustainably.

Why reduce carbon emissions?

Current techniques of hydrogen production produce greenhouse gases, raising sustainability issues. The most used method for generating hydrogen is Steam Methane Reforming (SMR), accounting for 96% of hydrogen production (Rocky Mountain Institute, 2020). However, this process uses fossil and fuels and results in the formation of methane and carbon dioxide, both noteworthy greenhouse gases. According to the prediction of the IPCC in their sixth report, an emissions scenario without altering our current trajectory would result in a concentration of carbon dioxide of 700 parts per million by the end of this century (IPCC, 2021). The resulting global mean surface temperature rise to that concentration is roughly 4 degrees Celsius by the end of the 21st century (IPCC, 2021). This would have devastating effects on agriculture, economies, and coastal areas. In addition, more substantial carbon emissions can partially melt ice sheets and glaciers and warm the oceans, thus increasing the sea levels.

Why is Energy Storage important?

As countries move towards more renewable energy portfolios to work towards sustainability, energy storage technology will rise. In future energy scenarios with more wind and solar resources used for electricity production, the intermittency of electricity production will increase. The more significant gaps between electricity production and consumption raise the need for storage capacity on the grid. Hydrogen technology offers viable long-term storage by employing electrolysis to capture and store hydrogen during excess electricity production and later use hydrogen to power fuel cells to produce electricity during shortages. In this way, hydrogen technology can help usher in largely decarbonized production by providing storage needed to accommodate the intermittent nature of renewable energy.

What is the potential application of hydrogen in Local Transportation?

This leads to our motivation being tied locally to the Ithaca, NY area. The TCAT (Thompkins County Area Transit) public transportation system has a large fleet of buses that can switch over to hydrogen fuel cell electric vehicles if a production and refueling station is large enough to support its operations. One major obstacle to hydrogen adoption in the transportation sector is the limited availability of refueling locations. More stations are needed if hydrogen-fueled transportation becomes viable for the region. We see an opportunity to repurpose the Emerson Plant on South Hill in Ithaca into a hub for hydrogen production, storage, and bus/truck refueling. This plant with 17.5 acres of floor space has been vacant and underutilized since 2009 (Akhigbe, 2011). The existing building space could be used for the hub of this project in our investigation to incorporate hydrogen in the energy portfolio of the Ithaca area.

Our energy-hungry world needs more sustainable sources of energy. Hydrogen technology offers potential solutions for the greater incorporation of renewable energy into the energy portfolios of deeply decarbonized energy markets. It is a tool in the toolbox of renewable energy for storage, transportation, and electrification. This analysis aims to be a guiding document discussing current costs, limitations, and usefulness of hydrogen technology.

1.2. Project scope and objectives

Project Scope:

The project's scope is to understand the potential of setting up the Hydrogen Fuel cell plant at the Chainworks Emerson Plant in Ithaca. We would evaluate the sources of hydrogen generation here in Ithaca/NY state and subsequent storage opportunities in the plant area. For generating hydrogen, we would be using renewable energy sources to make our entire system robust and sustainable with zero CO_2 emissions.

Objectives:

The project's primary objective is to make efficient use of the Chain works Emerson Plant area. In addition, we want to explore the potential applications of hydrogen in Ithaca and alongside NY state.

Besides, we need to consider reducing the use of traditional fossil fuels and achieve sustainable development goals as much as possible through a hydrogen energy-based transportation system. At the same time, we also need to improve economic efficiency as much as possible and have higher competitiveness compared with other products of the same type.

1.3. Limitations and Challenges

Hydrogen technology has its limitations because it is still not implemented at a large scale. Below, we have listed down the limitations concerning technology and project:

Limitations of the technology:

- Precious metals such as platinum and iridium are typically required, which means that the initial cost of fuel cells (and electrolyzers) can be high.
- Hydrogen is a highly flammable fuel source, which brings understandable safety concerns. Hydrogen gas burns in air at concentrations ranging from 4 to 75%.
- Hydrogen in vehicles must be compressed in expensive high-pressure tanks, which requires energy.
- The cost of hydrogen transportation is high.
- Most of the fuel cell used is not suitable for our target.
- The conversion of solar and wind energy into hydrogen energy is inefficient.
- So far, there has not been an exceptionally high cost of storing hydrogen safely.

Limitations of the project:

- The wind and solar data used to calculate solar and wind energy is based on NY state data.
- We recognize that the cost of energy production is of utmost importance in market incorporation. Hydrogen is still in its infancy stage of development and adoption. As a result, it is disadvantaged due to a lack of economies of scale compared to conventional technologies and even other renewables.

1.4. Project timeline:

The following table shows our project timeline and major milestones:

Month	Task	Start date	End date
September	Defining Project scope/motivation/limitations	09/01/2021	09/15/2021
September/October	Market Analysis	09/15/2021	10/15/2021
October	Solar Harvesting	10/1/2021	10/30/2021
October/November	Wind Harvesting	10/15/2021	11/15/2021
November	Studying Electrolysers	11/1/2021	11/15/2021
November	Hydrogen storage	11/15/2021	11/30/2021
November/December	Hydrogen fuel cells	11/15/2021	12/1/2021
November/December	Applications and future work	11/15/2021	12/7/2021

Table 1.4.a Project timeline

We efficiently met most of our deadlines due to impressive team-coordination and project management skills. Our team was divided into subgroups of 2-2-2 each for various activities to increase the quality of work while working collaboratively. At times, we deviated from this structure and pursued research more individually given the great variety of tasks and pieces of the project. We've also developed a final presentation which summarizes most of our findings in this project.

2. Market Analysis:

2.1. Energy consumption in India, China, and the US

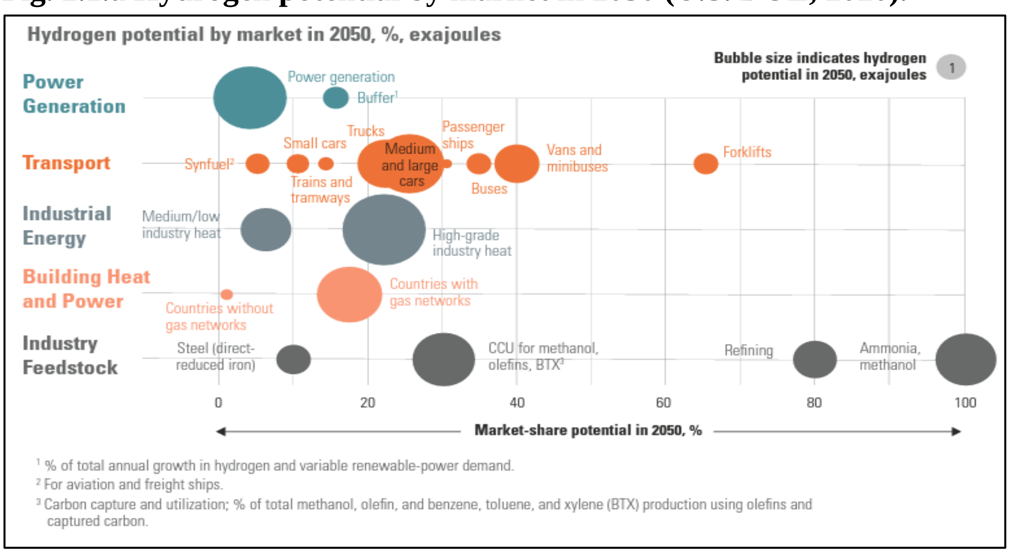
The energy demand and consumption in the world is increasing at an unprecedented speed. The OECD and non-OECD countries struggle to meet their energy demands and thus have started the transition towards more sustainable sources of energy. In the section below, we are going to discuss energy consumption trends in the US, China, and India.

U.S.

Hydrogen has the to mitigate the effects of a changing climate by diversifying the energy production and storage options available. The U.S. market has particular significance because of its large economic power and large consumption of energy. This makes the incorporation of hydrogen technology in the U.S. energy portfolio both poignant and impactful. It is therefore of use to know where and how hydrogen technology may have applications in energy and industrial sectors of the economy.

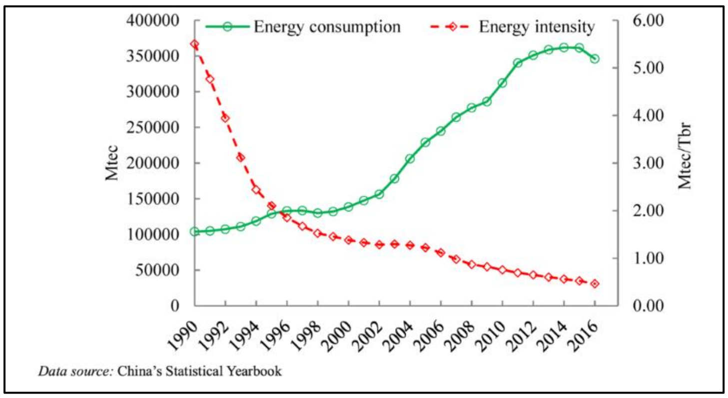
Currently, hydrogen development is experiencing a rapid expansion in both policy initiatives and project development. The IEA recommends focusing on promising areas of growth--decarbonizing a range of sectors by taking advantage of hydrogen's versatility (U.S. DOE, 2020). Hydrogen can help decarbonize sectors that struggle to reduce emissions. These sectors include long-range transportation and chemical, iron, and steel industries. As seen in Figure 2.1.a below, hydrogen holds the highest potential for market incorporation in industrial feedstock applications. In addition, there is significant potential for hydrogen to be used in the transportation sector for a variety of uses, most notably including trucks, larger vehicles, and forklifts (U.S. DOE, 2020). Hydrogen also holds significant potential for combined heat and power in delivering heat for both industrial and residential needs.

Fig. 2.1.a Hydrogen potential by market in 2050 (U.S. DOE, 2020).



China

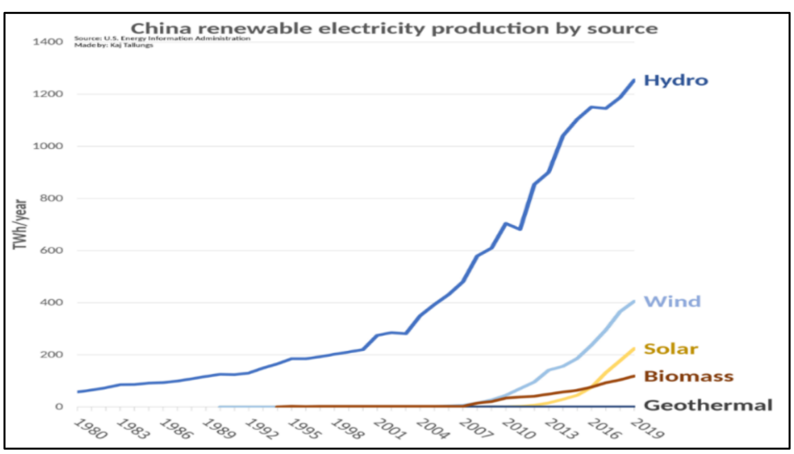
Since the reform in 1978, the amount of energy consumption in China has been rising dramatically. The energy consumption in China is increasing at an annual growth rate of 4.84%. Particularly, its growth mode can be divided into three phases: (i) 1990–2001, in which energy consumption grows much slowly; (ii) 2002–2012, where energy consumption manifests a sharp growth pattern; (iii) 2013–2016, in which energy consumption maintains almost stable, and even drops after 2015. At present, China has been the largest carbon emitter and energy consumer in the worldwide (Lin and Du, 2015), contributing to 22.9% of global energy consumption and 27.3% of global carbon emissions (Zhang et al., 2017).



China's hydrogen energy industry is taking off due to the investments over the past five years, as the country pushes towards peaking emissions by 2030 and reaching carbon neutrality by 2060.The price of hydrogen has dropped by 50%

Fig. 2.1.b Energy consumption and energy intensity in China over 1990-2016

Renewable energy such as hydro, biofuels and wastes, wind, heat power, and solar have been widely applied in China. In recent years, renewable energy consumption has been increasing. The primary liquid biofuels still account for more than 60 percent. Moreover, it generally is used in residential, commercial and public services, transport and industry and most of them fall to residential areas. The renewable energy structure and the distribution structure of consumption are unbalancing, which will have an influence on low carbon emissions. Fig. 2.1.c China renewable electricity production by source



India

India is a major force in the global energy economy. Energy consumption has more than doubled since 2000, propelled upwards by a growing population – soon to be the world’s largest – and a period of rapid economic growth. India’s continued industrialization and urbanization will make huge demands of its energy sector and its policy makers. Energy use on a per capita basis is well under half the global average, and there are widespread differences in energy use and the quality of service across states and between rural and urban areas. The affordability and reliability of energy supply are key concerns for India’s consumers.

Total energy consumption per capita in 2020 is still about 0.7 toe (ton of oil equivalent), half the Asian average. Per capita electricity consumption will reach 860 kilowatt-hours in 2020, about two-thirds of the Asian average. Total energy consumption decreased by 3.4% to 908 Mtoe in 2020 due to the COVID-19 crisis. During 2010-2019, it grew rapidly (+3.3%/ year).

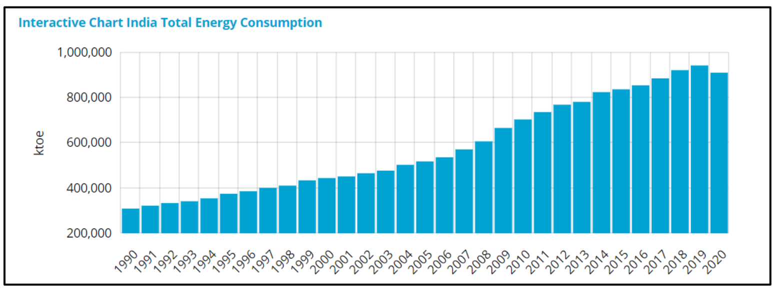
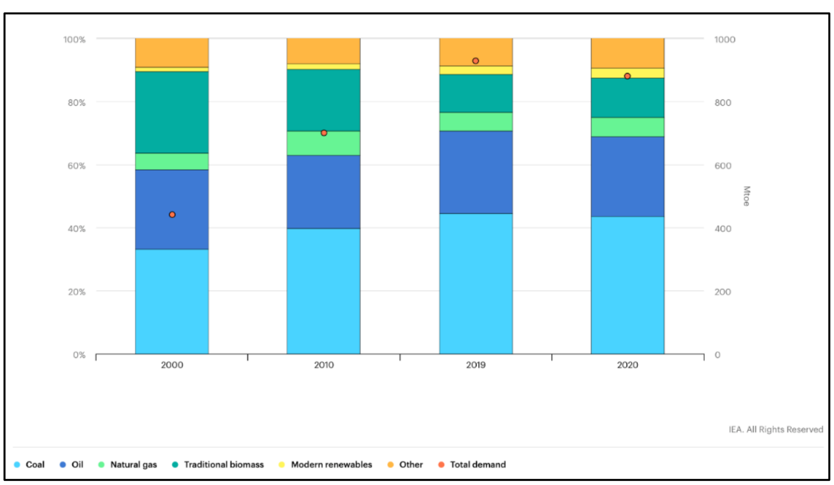


Fig. 2.1.d India total energy consumption, 1990-2020

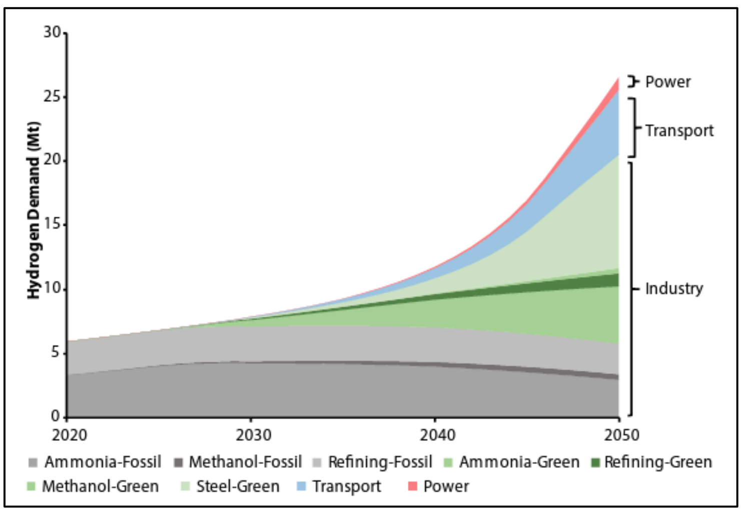
Over 80%of India’s energy needs are met by three fuels: coal, oil and solid biomass. Coal has underpinned the expansion of electricity generation and industry and remains the largest single fuel in the energy mix. Oil consumption and imports have grown rapidly on account of rising vehicle ownership and road transport use. Biomass, primarily fuelwood, makes up a declining share of the energy mix, but is still widely used as a cooking fuel. Despite recent success in expanding coverage of LPG in rural areas, 660 million Indians have not fully switched to modern, clean cooking fuels or technologies. Fig. 2.1.e Total primary energy demand in India, 2000-2020



Natural gas and modern renewable sources of energy have started to gain ground and were least affected by the effects of the Covid-19 pandemic in 2020. The rise of solar PV in particular has been spectacular; the resource potential is huge, ambitions are high, and policy support and technology cost reductions have quickly made it the cheapest option for new power generation.

India has a large potential to incorporate hydrogen technology into their markets. Currently, 6 metric tonnes of hydrogen are produced annually in India with expectations of a 5-fold increase by 2050 (Hall, et al. 2020). It is expected that a large demand for hydrogen in existing refinery and fertilizer industries will drive cost down of technology. Hydrogen also has a role to play in the transportation and energy storage sectors. By 2030, the costs of green hydrogen are expected to fall by 50%, low enough to be competitive with other methods of hydrogen production (Hall, et al., 2020). Fig 2.1.f shows expected hydrogen demand in India for a low-carbon scenario.

Figure 2.1.f Hydrogen demand forecast by sector and production type in 2050 (Hall, et. al., 2020).



Hydrogen technology is not a be-all-end-all technology. There are other competing and complementing technologies in batteries, fossil fuels, and other energy sources. Hydrogen has a role to play in specific sectors. Hydrogen will is best suited for long-distance heavy trucking applications, but will struggle to gain traction against BEVs in smaller vehicles. The need for hydrogen in ammonia and steel production is large. Both industries are expected to be the drivers of hydrogen technology incorporation and cost reduction (Hall, et al. 2020). It is expected that hydrogen technology will be first implemented in pockets of industry before becoming more widely utilized. Hydrogen is not expected, however, to become a dominant technology in industrial heat production. Thus, electrification of buildings in India is the proposed route to decarbonization in many cases. Hydrogen will also play an important role in providing energy storage in electricity markets. Currently, battery technology can provide functional storage for electricity. Once India's electricity market reaches 60-80% penetration of variable renewable energy, hydrogen storage technology is then expected to have a role to play in absorbing electricity during periods of high-production and low-cost (Hall, et al., 2020).

Table 2.1.a The role of hydrogen by sector in India (Hall, et al., 2020).

Sector	Use-Case	2020s	2030s	2040s
Transport	Light-duty passenger and freight transport	BEVs competitive with both FCEVs and ICEs	BEVs competitive with both FCEVs and ICEs	BEVs competitive with both FCEVs and ICEs.
	Short-distance, regular-route heavy-duty transport	BEVs becoming competitive with ICEs. FCEVs not competitive.	BEVs competitive with both FCEVs and ICEs.	BEVs competitive with both FCEVs and ICEs.
	Very long-distance heavy-duty freight transport	ICEs competitive.	FCEVs and BEVs becoming competitive with ICE.	FCEVs likely to be competitive with ICE. BEVs partly competitive.
Industry	Ammonia production	Fossil fuels competitive. H_2 becoming competitive.	H_2 competitive (ammonia and refineries) and partly competitive (steel).	H_2 from renewables competitive.
	Steel production			
	Refineries hydrogen demand			
	Methanol production	Fossil fuels competitive.	Fossil fuels competitive. H_2 partially competitive.	Fossil fuels competitive. H_2 partially competitive.
	Industrial heat	Fossil fuels competitive. Direct electrification partly competitive.	Fossil fuels competitive. Electrification increasingly competitive.	Fossil fuels likely to be competitive. H_2 and direct electrification may be partly competitive.
Electricity storage	Short-term (daily) storage	Li-ion batteries competitive.	Li-ion batteries competitive.	Li-ion batteries competitive.
	Short-term (weekly/monthly/ seasonal) storage	Long-term balancing from fossil and hydro. Long-term storage needs minimal.	H_2 becoming competitive but minimal need as wind and solar still below 60-80%.	H_2 competitive. Long-term storage required in a high wind and solar system.

Legend: Brown = fossil fuels dominate. Yellow = direct electrification without using H_2 as an energy vector, e.g. battery electric vehicles or li-ion batteries in electricity storage. Blue = hydrogen. Green = mixed paradigm with several technologies including hydrogen.

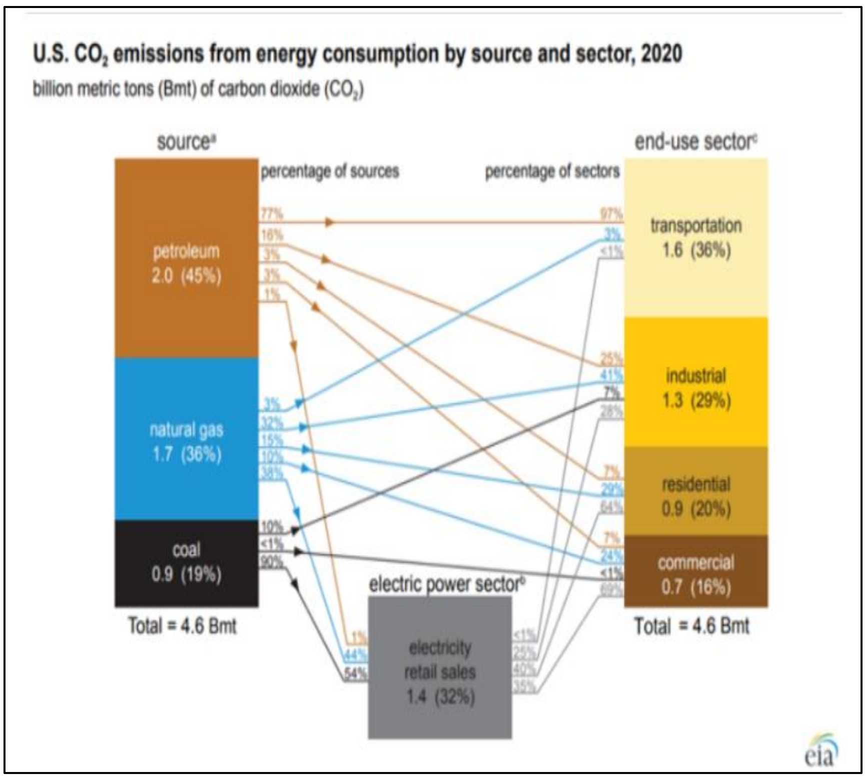
2.2. Energy demand as per different modes of transport

This chart shows the energy consumption (in gasoline gallon equivalents [GGEs]) of U.S. transportation in 2018 by mode and fuel type. In most cases, each mode of transportation is dominated by a different fuel type.

Table 2.2.a Energy Use by Transportation Mode and Fuel Type in 2018 (AFDC, 2021)

Energy Use by Transportation Mode and Fuel Type in 2018 (Billion GGEs per Year)								
Mode	**Gasoline**	**Diesel**	**Propane**	**Jet Fuel**	**Residual Fuel Oil**	**Natural Gas**	**Electricity**	**Total**
Light-Duty Vehicles	116.410	3.519	0.426	0.000	0.000	0.000	0.076	**120.431**
Medium/Heavy Trucks and Buses	5.130	46.504	0.168	0.000	0.000	0.201	0.002	**52.004**
Air	0.211	0.000	0.000	18.441	0.000	0.000	0.000	**18.652**
Water	1.356	2.628	0.000	0.000	4.875	0.000	0.000	**8.859**
Pipeline	0.000	0.000	0.000	0.000	0.000	7.036	0.659	**7.695**
Rail	0.000	4.235	0.000	0.000	0.000	0.000	0.191	**4.425**

In the United States, the first two most energy-consuming types：1. light-duty vehicles mainly use gasoline as the main energy source. 2. Medium/heavy trucks and buses mainly use diesel energy. Fig. 2.2.a US emissions from energy consumption by source and sector (EIA, 2020).



In 2020, U.S. petroleum consumption will account for 2.0 billion metric tonnes (Bmt) of energy-related carbon dioxide emissions, accounting for approximately 45% of the U.S. total. In 2020, about 77% of petroleum CO2 emissions will occur in the transportation sector. (EIA, 2020)

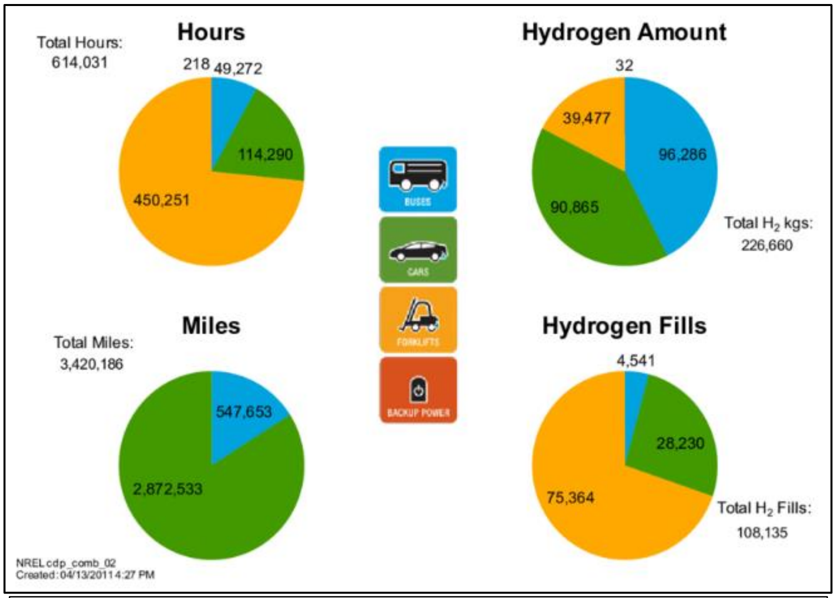


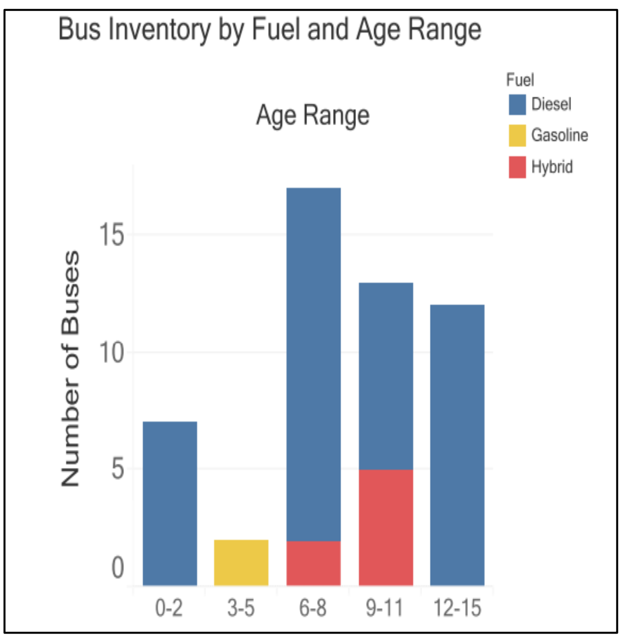
Fig. 2.2.b US hydrogen usage status (EIA, 2020)

Approximately half of Americans live in areas where air pollution levels are high enough to harm public health and the environment. Nitrogen-oxides, hydrocarbons,and particulate matter emitted by gasoline and diesel vehicles are the primary sources of this pollution. Hydrogen fuel cell vehicles will not emit these harmful substances, only water, and warm air, (EIA, 2020).

Environmental and health benefits can also be seen if hydrogen is produced from low-emission or zero-emission sources, such as wind, solar, nuclear, and fossil fuels with advanced emission control and carbon storage technologies. Since the transportation industry accounts for about one-third of US carbon dioxide emissions, using these sources to produce hydrogen for transportation can reduce greenhouse gas emissions.

Hydrogen is expected to help strengthen national energy security, save fuel, and diversify our transportation energy options to build more flexible systems.

Ithaca Buses System Energy Demand



According to the 2017 annual report of TCAT, the total service distance by buses in 2017 is 1,579,450 miles. If the average gasoline consumption per mile is assumed as 0.69L (BTS Transportation Statistics Annual Report 2020), and the efficient energy generated by the consumption of a litter of gasoline is about 10.35MJ, the total energy consumption for buses in TCAT can be roughly estimated as 1.13*10^13J.

Figure 2.2.c Bus inventory by fuel and age range

2.3. Hydrogen generation

Energy carriers allow the transport of energy in a usable form from one place to another. Hydrogen, like electricity, is an energy carrier that must be produced from another substance. Hydrogen can be produced—separated—from a variety of sources including water, fossil fuels, or biomass and used as a source of energy or fuel. The U.S. produces about nine million tons of hydrogen per year. Hydrogen has the highest energy content of any common fuel by weight, but very low energy for its volume, so new technology is needed to store and transport it. (About three times more than gasoline) (1)

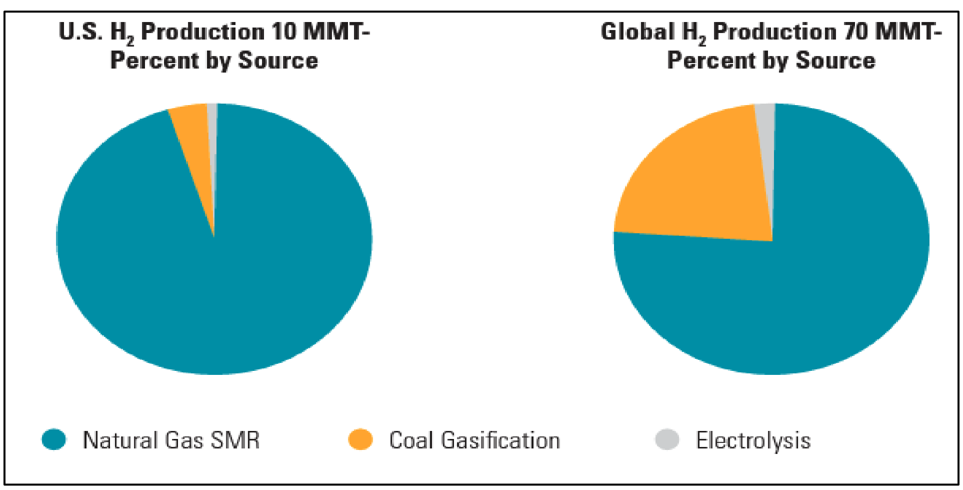
Does hydrogen exist freely in nature?

Hydrogen is also the most abundant element in the universe. Hydrogen has only 1 electron so it is not stable and cannot exist independently. It either loses an electron, gains an electron, or share its electrons with another Hydrogen atom.

What are the traditional sources of hydrogen generation?

Currently, there are many ways of generating hydrogen. The United States produces roughly 10 million metric tons of hydrogen annually. The most common in the industry is a process called steam methane reforming (SMR). SMR is responsible for 95% of all hydrogen produced domestically. Partial oxidation, also known as coal gasification accounts for 4% of U.S. production, leaving 1% of production from electrolysis (U.S. DOE, 2020). Globally, partial oxidation is more common, particularly in China.

Fig 2.3.a Domestic and Global Hydrogen Production by Source Type



Hydrogen can be produced from different sources. Currently, hydrogen is produced from fossil fuels, specifically natural gas. Fossil fuels can be reformed to release the hydrogen from their hydrocarbon molecules and are the source of most of the hydrogen currently made in the United States. Combining these processes with carbon capture, utilization, and storage will reduce the carbon dioxide emissions. Natural gas reforming is an advanced and mature hydrogen production process that builds upon the existing natural gas infrastructure. Today 95% of the hydrogen produced in the United States is made by natural gas reforming in large central plants. (2). Most hydrogen production today is by steam reforming natural gas. But natural gas is already a good fuel and one that is rapidly becoming scarcer and more expensive. It is also a fossil fuel, so the carbon dioxide released in the reformation process adds to the greenhouse effect. (3)

Natural gas contains methane (CH_4) that can be used to produce hydrogen with thermal processes, such as steam-methane reformation and partial oxidation.

a. Steam-methane reformation:

Most hydrogen produced today in the United States is made via steam-methane reforming, a mature production process in which high-temperature steam (700°C–1,000°C) is used to produce hydrogen from a methane source, such as natural gas. In steam-methane reforming, methane reacts with steam under 3–25 bar pressure (1 bar = 14.5 psi) in the presence of a catalyst to produce hydrogen, carbon monoxide, and a relatively small amount of carbon dioxide. Steam reforming is endothermic—that is, heat must be supplied to the process for the reaction to proceed.

Subsequently, in what is called the "water-gas shift reaction," the carbon monoxide and steam are reacted using a catalyst to produce carbon dioxide and more hydrogen. In a final process step called "pressure-swing adsorption," carbon dioxide and other impurities are removed from the gas stream, leaving essentially pure hydrogen. Steam reforming can also be used to produce hydrogen from other fuels, such as ethanol, propane, or even gasoline.

Steam-methane reforming reaction	Water-gas shift reaction
$CH_4 + H_2O$ (+ heat) $\rightarrow CO + 3H_2$	$CO + H_2O \rightarrow CO_2 + H_2$ (+ small amount of heat)

b. Partial Oxidation:

In partial oxidation, the methane and other hydrocarbons in natural gas react with a limited amount of oxygen (typically from air) that is not enough to completely oxidize the hydrocarbons to carbon dioxide and water. With less than the stoichiometric amount of oxygen available, the reaction products contain primarily hydrogen and carbon monoxide (and nitrogen, if the reaction is carried out with air rather than pure oxygen), and a relatively small amount of carbon dioxide and other compounds. Subsequently, in a water-gas shift reaction, the carbon monoxide reacts with water to form carbon dioxide and more hydrogen.

Partial oxidation is an exothermic process—it gives off heat. The process is, typically, much faster than steam reforming and requires a smaller reactor vessel. As can be seen in chemical reactions of partial oxidation, this process initially produces less hydrogen per unit of the input fuel than is obtained by steam reforming of the same fuel.

Partial oxidation of methane reaction   Water-gas shift reaction
$CH_4 + ½O_2 \rightarrow CO + 2H_2$ (+ heat) $CO + H_2O \rightarrow CO_2 + H_2$ (+ small amount of heat) (4)

What are the new sources of hydrogen generation?

a. Electrolysers:

Electrolysis is a promising option for carbon-free hydrogen production from renewable and nuclear resources. Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyzer. Electrolyzers can range in size from small, appliance-size equipment that is well-suited for small-scale distributed hydrogen production to large-scale, central production facilities that could be tied directly to renewable or other non-greenhouse-gas-emitting forms of electricity production.

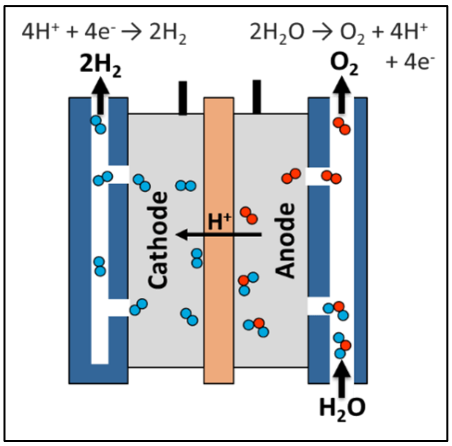


Figure 2.3.b Electrolyser

While electrolysis makes up a small share of the hydrogen generation market, electrolysis holds the key to unlocking green hydrogen production. The technologies for water electrolysis which are presently considered viable include: Alkaline Electrolysis (AEL); Proton Exchange Membrane (PEM); and to a lesser extent Solid Oxide Electrolysis (SOEL) (Burton, et al., 2021).

How Does it Work?

Like fuel cells, electrolyzers consist of an anode and a cathode separated by an electrolyte. Different electrolyzers function in different ways, mainly due to the different type of electrolyte material involved and the ionic species it conducts.

Alkaline Electrolysis is the most mature electrolysis method and is characterized by low capital costs with flexibility to operate from 10%-100% rated capacity. Alkaline electrolysis has been used since the 1920s for the production of fertilizer and chlorine, but was replaced by cheaper hydrogen generation methods of SMR and in the 1970s (IEA, 2019).

Proton Exchange Membrane Electrolysis was developed in the 1960s, using only water as an electrolyte solution. This avoids the recycling of the potassium hydroxide electrolyte solution needed in AEL. PEM electrolysis relies on platinum and iridium, raising the capital cost of these systems. However, they are roughly twice as compact than their AEL counterparts, can operate from 0-160% of design capacity, and operate at higher pressures (IEA, 2019). This operation at higher pressures is particularly attractive as the energy required for liquefication of hydrogen is equivalent to 30% of the potential energy of the stored hydrogen (Burton, et al., 2021).

In addition to AEL and PEM, solid oxide electrolysis has seen attention in studies and the industry. Solid oxide electrolysis operates at high temperatures, using steam for electrolysis. It employs ceramics for the electrolyte. SOEL has high electrical efficiencies and can be run in reverse, acting as a fuel cell. Waste heat can be used to generate steam needed for electrolysis. SOEL technology has yet to become commercially viable and suffers from high degradation of the electrolyzer because of such high operating temperatures (IEA, 2019).

Operational conditions	AEL	PEM	SOEL
Temperature (°C) [59,62,63]	40–90	20–100	650–1000
Pressure (bar) [59,64]	<30	<200	<20
Cell area (m^2) [59,64]	<4	<0.13	<0.06
Current density (Acm^{-2}) [59,62,63]	0.2–0.4	0.6–2.0	0.3–2.0
Voltage (V) [62,63]	1.8–2.4	1.8–2.2	0.7–1.5
Production (Nm^3/h) [59]	<1400	<400	<10
Gas purity (%) [64,65]	>99.5%	>99.99	>99.9
Stack energy consumption (kWh/Nm^3) [59,62,64]	4.2–5.9	4.2–5.5	>3
System energy consumption (kWh/Nm^3) [59,66]	4.5–6.6	4.2–6.6	3.7–3.9
Stack efficiency (% LHV) [59,62,64]	63–71	60–68	100
System efficiency (% LHV) [59]	51–60	46–60	76–81
Lifetime of stack (kh) [59,66]	60–120	60–100	8–20
Degradation (%/a) [59]	0.25–1.5	0.5–2.5	3–50
Capital cost (USD/kW) [59,66]	880–1650	1540–2550	>2000
Maintenance cost (% of investment/year) [59]	2–3	3–5	n.a.
Advantages [67]	Low capital cost; stable operation	High H_2 purity, fast start-up; compact system	High efficiency; low capital cost
Disadvantages [67]	Corrosive system; low H_2 purity; slow start-up	High cost of membranes and electrodes; high pressure; acidic	Instability causing safety issues
Technology maturity [67,68]	Commercial	Near commercial	Demonstration

Figure 2.3.c Characteristics of Alkaline, Proton Exchange Membrane, and Solid Oxide electrolysis.

Why Is This Pathway Being Considered?

Electrolysis is a leading hydrogen production pathway to achieve the Hydrogen Energy Earthshot goal of reducing the cost of clean hydrogen by 80% to $1 per 1 kilogram in 1 decade ("1 1 1"). Hydrogen produced via electrolysis can result in zero greenhouse gas emissions, depending on the source of the electricity used. The source of the required electricity—including its cost and efficiency, as well as emissions resulting from electricity generation—must be considered when evaluating the benefits and economic viability of hydrogen production via electrolysis. In many regions of the country, today's power grid is not ideal for providing the electricity required for electrolysis because of the greenhouse gases released and the amount of fuel required due to the low efficiency of the electricity generation process. Hydrogen production via electrolysis is being pursued for renewable (wind, solar, hydro, geothermal) and nuclear energy options. These hydrogen production pathways result in virtually zero greenhouse gas and criteria pollutant emissions; however, the production cost needs to be decreased significantly to be competitive with more mature carbon-based pathways such as natural gas reforming.

Potential for synergy with renewable energy power generation. Hydrogen production via electrolysis may offer opportunities for synergy with dynamic and intermittent power generation, which is characteristic of some renewable energy technologies. For example, though the cost of wind power has continued to drop, the inherent variability of wind is an impediment to the effective use of wind power. Hydrogen fuel and electric power generation could be integrated at a wind farm, allowing flexibility to shift production to best match resource availability with system operational needs and market factors. Also, in times of excess electricity production from wind farms, instead of curtailing the electricity as is commonly done, it is possible to use this excess electricity to produce hydrogen through electrolysis.

b. Liquid derived biomass

Liquids derived from biomass resources—including ethanol and bio-oils—can be reformed to produce hydrogen in a process similar to natural gas reforming. Biomass-derived liquids can be transported more easily than their biomass feedstocks, allowing for semi-central production or possibly distributed hydrogen production at fueling stations. Biomass-derived liquid reforming is a mid-term technology pathway.

How Does It Work?

Biomass resources can be converted to cellulosic ethanol, bio-oils, or other liquid biofuels. Some of these liquids may be transported at relatively low cost to a refueling station or other point of use and reformed to produce hydrogen. Others (for example, bio-oils) may be reformed on-site.

The process for reforming biomass-derived liquids to hydrogen is very similar to natural gas reforming and includes the following steps: The liquid fuel is reacted with steam at high temperatures in the presence of a catalyst to produce a reformate gas composed mostly of hydrogen, carbon monoxide, and some carbon dioxide.

Additional hydrogen and carbon dioxide are produced by reacting the carbon monoxide (created in the first step) with high-temperature steam in the "water-gas shift reaction."

Finally, the hydrogen is separated out and purified.

Steam reforming reaction (ethanol)
$C_2H_5OH + H_2O$ (+ heat) → $2CO + 4H_2$

Water-gas shift reaction
$CO + H_2O \rightarrow CO_2 + H_2$ (+ small amount of heat)

Biomass-derived liquids, such as ethanol and bio-oils, can be produced at large, central facilities located near the biomass source to take advantage of economies of scale and reduce the cost of transporting the solid biomass feedstock. The liquids have a high energy density and with some upgrading can be transported with minimal new delivery infrastructure and at relatively low cost to distributed refueling stations, semi-central production facilities, or stationary power sites for reforming to hydrogen.

c. Thermochemical water splitting

Thermochemical water splitting uses high temperatures—from concentrated solar power or from the waste heat of nuclear power reactions—and chemical reactions to produce hydrogen and oxygen from water. This is a long-term technology pathway, with potentially low or no greenhouse gas emissions.

How Does It Work?

Thermochemical water splitting processes use high-temperature heat (500°–2,000°C) to drive a series of chemical reactions that produce hydrogen. The chemicals used in the process are reused within each cycle, creating a closed loop that consumes only water and produces hydrogen and oxygen. The necessary high temperatures can be generated in the following ways:

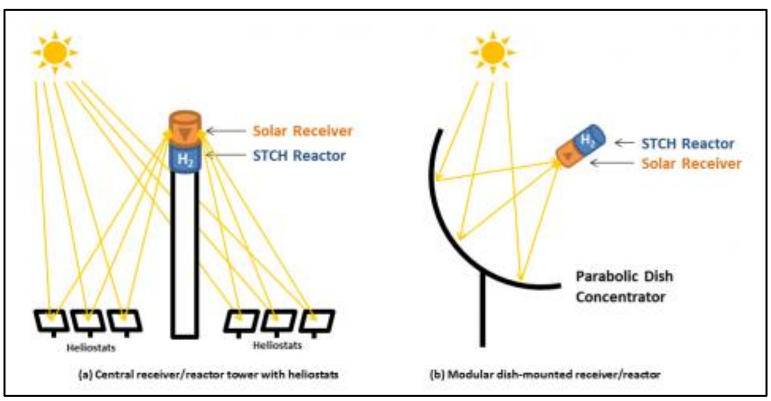


Figure 2.3.d Thermochemical water splitting

Numerous solar thermochemical water-splitting cycles have been investigated for hydrogen production, each with different sets of operating conditions, engineering challenges, and hydrogen production opportunities. In fact, more than 300 water-splitting cycles are described in the literature.

Two examples of thermochemical water splitting cycles, the "direct" two-step cerium oxide thermal cycle and the "hybrid" copper chloride cycle, are illustrated in Figure 2. Typically, direct cycles are less complex with fewer steps, but they require higher operating temperatures compared with the more complicated hybrid cycles.

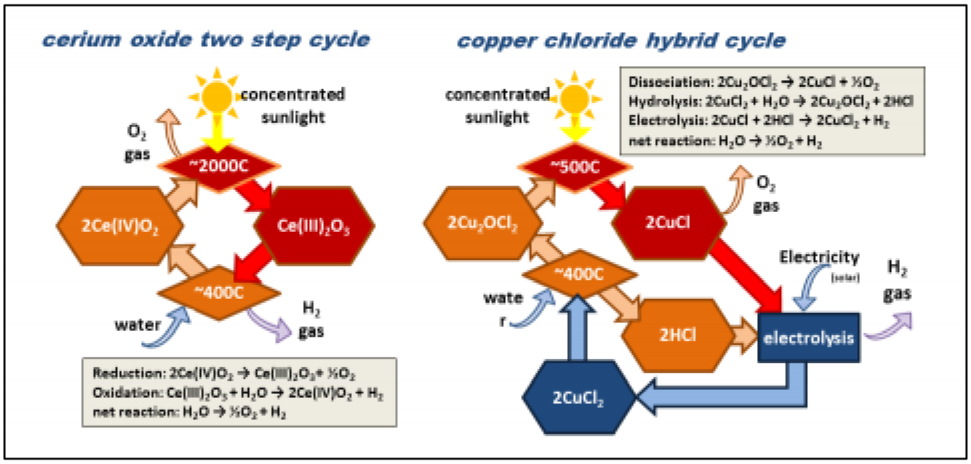


Figure 2.3.e Examples of thermochemical water splitting

d. Photoelectrochemical water splitting

In photoelectrochemical (PEC) water splitting, hydrogen is produced from water using sunlight and specialized semiconductors called photoelectrochemical materials, which use light energy to directly dissociate water molecules into hydrogen and oxygen. This is a long-term technology pathway, with the potential for low or no greenhouse gas emissions.

How Does it Work?

The PEC water splitting process uses semiconductor materials to convert solar energy directly to chemical energy in the form of hydrogen. The semiconductor materials used in the PEC process are like those used in photovoltaic solar electricity generation, but for PEC applications the semiconductor is immersed in a water-based electrolyte, where sunlight energizes the water-splitting process.

PEC reactors can be constructed in panel form (like photovoltaic panels) as electrode systems or as slurry-based particle systems, each approach with its own advantages and challenges. To date, panel systems have been the most widely studied, owing to the similarities with established photovoltaic panel technologies. Click on each figure title to see some different possible implementations of both the panel and slurry reactor concepts.

e. Photobiological hydrogen production

The photobiological hydrogen production process uses microorganisms and sunlight to turn water, and sometimes organic matter, into hydrogen. This is a longer-term technology pathway in the early stages of research that has a long-term potential for sustainable hydrogen production with low environmental impact.

How Does it Work?

In photolytic biological systems, microorganisms—such as green microalgae or cyanobacteria—use sunlight to split water into oxygen and hydrogen ions. The hydrogen ions can be combined through direct or indirect routes and released as hydrogen gas. Challenges for this pathway include low rates of hydrogen production and the fact that splitting water also produces oxygen, which quickly inhibits the hydrogen production reaction and can be a safety issue when mixed with hydrogen in certain concentrations. Researchers are working to develop methods to allow the microbes to produce hydrogen for longer periods of time and to increase the rate of hydrogen production.

Some photosynthetic microbes use sunlight as the driver to break down organic matter, releasing hydrogen. This is known as photo fermentative hydrogen production. Some of the major challenges of this pathway include a very low hydrogen production rate and low solar-to-hydrogen efficiency, making it a commercially unviable pathway for hydrogen production currently.

How much energy is wasted in generating hydrogen?

Efficiency of production methods is as follows:

Technology	Feed stock	Efficiency	Maturity	Reference
Steam reforming	Hydrocarbons	70–85%[a]	Commercial	[31]
Partial oxidation	Hydrocarbons	60–75%[a]	Commercial	[31]
Autothermal reforming	Hydrocarbons	60–75%[a]	Near term	[31]
Plasma reforming	Hydrocarbons	9–85%[b]	Long term	[74]
Aqueous phase reforming	Carbohydrates	35–55%[a]	Med. term	[99]
Ammonia reforming	Ammonia	NA	Near term	
Biomass gasification	Biomass	35–50%[a]	Commercial	[9], [20], [127]
Photolysis	Sunlight + water	0.5%[c]	Long term	[161]
Dark fermentation	Biomass	60–80%[d]	Long term	[9], [135]
Photo fermentation	Biomass + sunlight	0.1%[e]	Long term	[9], [20]
Microbial electrolysis cells	Biomass + electricity	78%[f]	Long term	[162]
Alkaline electrolyzer	H_2O + electricity	50–60%[g]	Commercial	[20], [159]
PEM electrolyzer	H_2O + electricity	55–70%[g]	Near term	[20], [159]
Solid oxide electrolysis cells	H_2O + electricity + heat	40–60%[h]	Med. Term	[127]
Thermochemical water splitting	H_2O + heat	NA	Long term	
Photoelectrochemical water splitting	H_2O + sunlight	12.4%[i]	Long term	[159], [186]

Table 2.3.a Efficiency of different methods

The global thermal and exergy efficiencies of the base-case system are 66.7% and 62.7%, respectively. Of the 37.3% of exergy not utilized within the system (un-used exergy), 81% is destroyed within the system and 19% exits in the exhaust stream.

2.4. Applications of Hydrogen fuel cells

The world is expecting a hydrogen revolution as Hydrogen Fuel cells possess a variety of applications. Here in this section, We are going to discuss about 4 main applications:

2.4.1. Forklifts

With the increasing popularity of electric forklifts, manufacturers strive to improve running time and performance to match or even surpass internal combustion engines (IC).Hydrogen is a viable alternative energy source. When it comes to material handling equipment, even cars, and factories, hydrogen fuel cells have proven to be a realistic alternative to the traditional ways of driving machinery and equipment today.

The Proton Exchange Membrane (PEM) fuel cell is currently the most viable type for powering industrial equipment such as forklifts. Similar to batteries, PEM fuel cells use cathodes, anodes, and electrolytes to transfer electrons along an electrical path to power forklifts. However, unlike lead-acid batteries, this process only uses hydrogen and oxygen that is naturally present in the atmosphere.

Table 2.3.a Efficiency of different methods

The global thermal and exergy efficiencies of the base-case system are 66.7% and 62.7%, respectively. Of the 37.3% of exergy not utilized within the system (un-used exergy), 81% is destroyed within the system and 19% exits in the exhaust stream.

Figure 2.4.a Fuel Cell Forklift

Advantages of using Hydrogen powered Forklifts:

Battery changes are no longer necessary:

Current battery electric forklifts run times are governed by the storage capacity of the unit battery. Forklifts that are required to operate over an extended shift may require a mid-shift battery change to ensure the unit is able to operate until the end of the prescribed shift. Whilst undertaking the battery change both the forklift and its operator are removed from operations leading to a downturn in productivity and efficiency.

This can have a large overall impact on operations if multiple battery changes are required at the same time removing multiple forklifts and operators from operations for an extended period of time.

Hydrogen forklifts can be quickly and efficiently refueled from a bowser system very similar how we fill up vehicles at a service station currently. Refueling of hydrogen forklifts can take as little as three minutes compared to up to 20 minutes for current lead acid batteries. Companies may also experience capital equipment cost savings as battery charging equipment and battery lifting equipment such as cranes will not need to be purchased and installed within the facility. (2)

Reclaim warehouse space:

Depending on the size of forklift fleet being operated and how many battery chargers are installed to keep units running across long shift (particularly for 24/7 operations) a large amount of floor space within a facility may need to be dedicated to a battery room fitted with all the necessary charging and changeover equipment. Important storage space may be tied up in the battery room that could be better utilized for the storage of products. Hydrogen storage and refueling equipment have a much smaller footprint and will occupy less vital storage space. (2)

2.4.2. Long distance trucking

Interest in hydrogen fuel cells as a sustainable source of clean energy is on the rise globally, and hydrogen fuel cells are widely seen as a viable, zero-emission option to power trucks, trains, ferries, and passenger vehicles. (1)

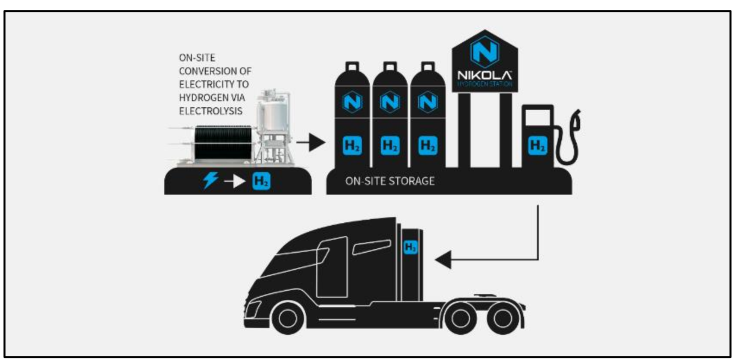
Fuel cell vehicles use the same basic electric drive system as battery trucks (and even have a battery), but because of their onboard hydrogen storage, fuel cell vehicles have a longer time frame, requiring fewer stops for long routes, and can drive faster and more the ability to lose goods with less risk.

The climate crisis requires us to decarbonize the global transportation system. To meet this requirement, the so-called solution has been to " electrify everything " for some time.

It needs to be clear that batteries may have a lot of meaning for certain elements of truck transportation. In fact, well-known companies in the field of electric vehicles, such as Tesla (Tesla), have launched a product that can solve the 300 to 500-mile medium-range driving range problem. However, especially for long-distance routes, there is a technology that is more suitable for this task: hydrogen fuel cells.

The high energy storage density offered by these hydrogen fuel cell-powered vehicles provides sufficient vehicle range to meet at least 95% of the daily routes based on preliminary analysis of data collected from U.S. Census survey results and real-world drive cycle data collection (3)

Given hydrogen fuel cell vehicle's zero tailpipe emission profile, areas with air quality issues—largely due to a concentration of heavy-duty diesel trucks—have become the ideal testing ground. More specifically, Southern California, which is home to the nation's largest seaport complex and worst air quality, has become the epicenter for fuel cell vehicle R&D projects. (2)



There are companies which are planning to have their own on-site hydrogen generation using renewable energy sources and eventually supply it to their clients for long distance hydrogen trucking.

Figure 2.4.b Refuelling structure

2.4.3. Stationary applications

The stationary sector ranges from small backup power systems to large residential, industrial and primary power systems, or for combined heat and power systems. Each of these stationary fuel cell systems provide reliable, clean and quiet power as well as improved efficiencies, resiliency, reduced emissions and lower energy costs. (1)

Fuel cells are highly efficient, typically reaching fuel to electricity efficiency of 60 percent, nearly double the efficiency of today's electric grid. Fuel cells also generate heat which, if captured, can increase overall energy efficiency to more than 90 percent. The heat produced by fuel cells can generate additional electricity through a turbine, provide heating directly to nearby buildings or facilities, and even cooling with the addition of an absorption chiller.(2)

As an example, fuel cells provided critical emergency backup power to telecommunications towers operating for hundreds of hours in both the Bahamas and the Northeast United States after Hurricane Sandy slammed the Caribbean and the East Coast in 2012. Fuel cells can offer significant cost advantages over battery-generator systems when shorter run-times of three days or less are sufficient. (1). At a local level, stationary fuel cells are used as part of uninterruptible power supply (UPS) systems, where continuous uptime is critical. Both hospitals and data centers are increasingly looking to hydrogen to meet their uninterruptible power supply needs. Recently, Microsoft made headlines with a successful test of its new hydrogen backup generators, running one data center's servers on nothing but hydrogen for two days. (3)

2.5. Deployment of hydrogen refueling infrastructure

2.5.1 Hydrogen Refueling Station Planning

Definition, Goal & Considerations

What is HRS Planning: consists of decisions on the technology type, number, locations and sizes (and the resulting utilization) of the stations to be deployed for meeting the hydrogen demand anticipated from a growing population of fuel cell vehicles in a given region (Nicholas and Ogden, 1983).

Goal: to minimize the expected system cost for given constraints and to provide guidance for deployment actions.

IEA (International Energy Agency) estimates investment costs for current hydrogen refueling stations in the range of $0.6-2 million for hydrogen at a pressure of 700 bar, and $0.15-1.6 million at 350 bar.

There is considerable scope of reducing the cost of hydrogen refueling stations by:

a. Scaling up the station size,
b. Reducing the station capital cost via mass production and process development of key components such as compressors, storage and onsite electrolyzers,
c. Improving the utilization of the station via growing demand.

Considerations: both supply (e.g., station technology performance and cost) and demand (e.g., where and how often refueling needs will occur). Especially for new types of infrastructure technologies it is important for planning to include issues such as permitting and compliance with codes and standards to reduce the likelihood of unanticipated delays or costs.

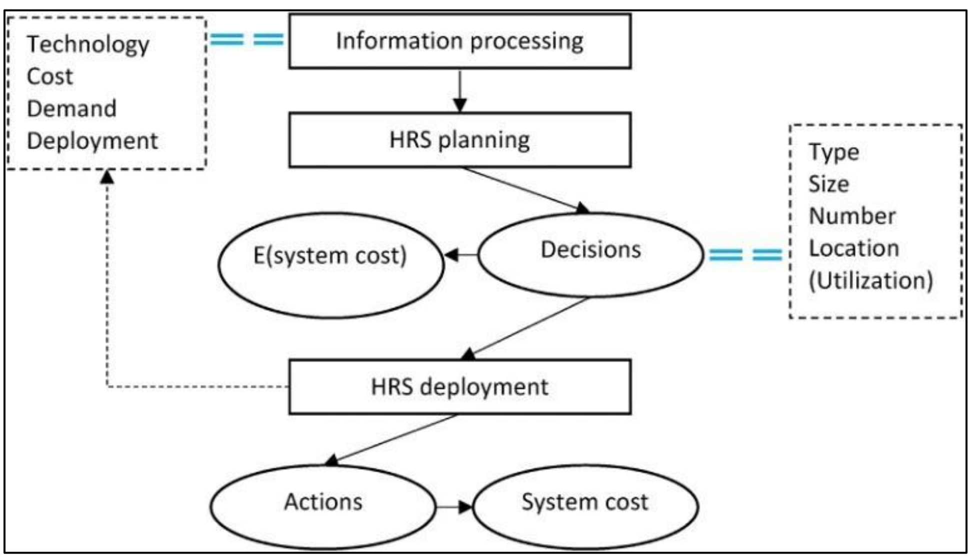


Figure 2.5.a HRS Planning Framework

(Rectangle with solid borders—processes, ovals—outcomes, rect with dashes borders--data)

Significance

Lack of refueling stations is a significant problem met by the users of HFCVs. It is the main reason for people to decide to no longer use HFCVs.

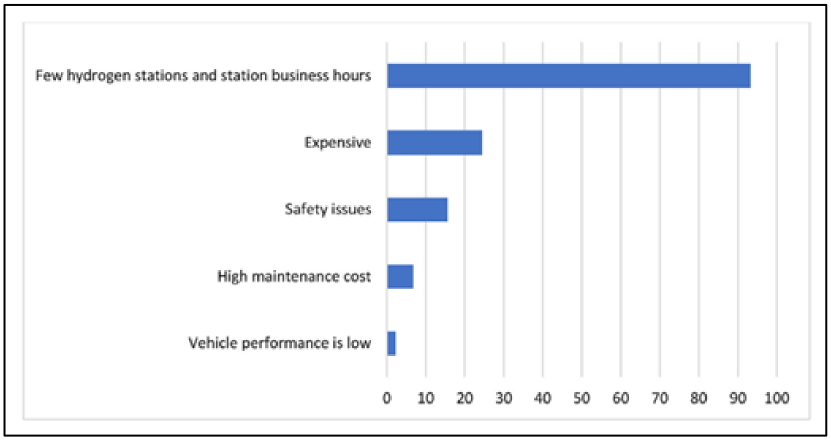


Figure 2.5.b Percentage of the private adopters who will replace HFCV when inquired, 'What is the reason of replacing current HFCV'

Core questions & Solution

Core questions: how many refueling stations to deploy? where to locate them?

Solution for location optimization -- P-median Model (maximum covering location problem)

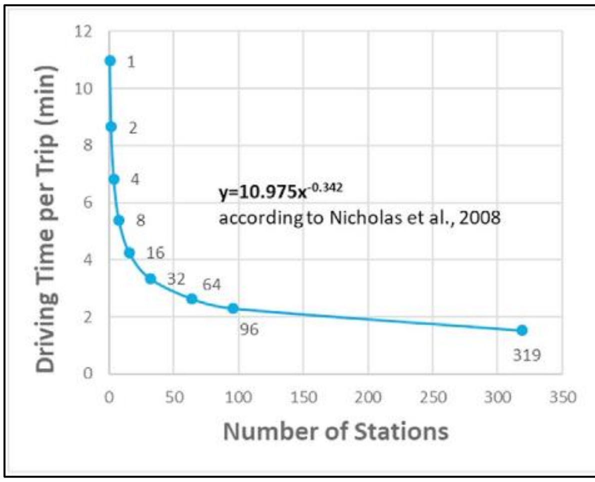
Objective: minimize the weighted average distance of refueling demand to the nearest station (Nicholas, Handy and Sperling, 2004) and maximize refueling convenience. The smaller this weighted average distance, the more accessible the HRS network is to FCV drivers. (distance is defined to be 0 if the actual distance is within a certain limit and 1 otherwise)

Demand origins determine the type of distance weight --> Where does hydrogen refueling demand originate from? Home and workplaces: weighted by population density.Traffic flows (Kim and Kuby, 2012): the p-median problem can be adapted by treating hydrogen demand clusters, rather than the general traffic in the region, as demand origins.

Potential constraints: station capacity, FCV driving range and land use (Ogden and Nicholas, 2011).

The capacity of each station located can be estimated based on the allocated hydrogen demand. The total station cost can then be calculated. When station capacity is also a decision variable, it raises the critical issue of economies of scale. In that case, a suitable objective is minimizing the total system cost, including station costs and the monetized refueling inconvenience determined by station location and numbers. For a given total hydrogen demand, more stations mean smaller average station sizes and thus higher station costs, but less refueling inconvenience.

Exponential relationship between refueling travel time and station number:



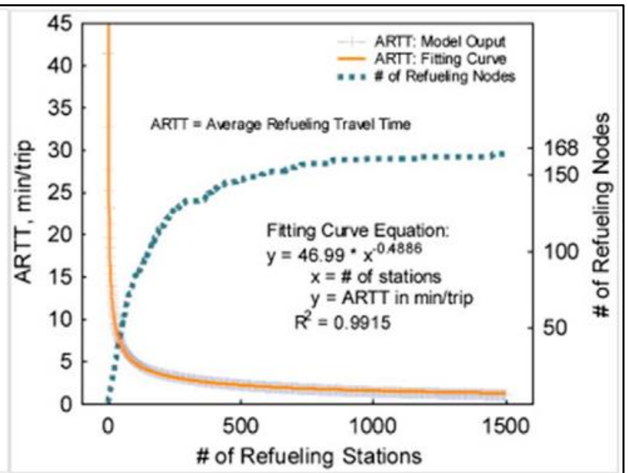


Figure 2.5.c **Figure 2.5.d**

2.5.2 Cost of refueling station

The two largest cost components are the compressor (which can be up to 60% of the total cost when the delivery pressure is 700 bar) to achieve the delivery pressure, and the storage tanks (which are relatively large due to lower hydrogen density). The actual cost of building a station varies considerably across countries, mainly as a result of different safety and permitting requirements. There are strong economies of scale. Increasing the capacity from 50 to 500 kgH2/day would be likely to reduce the specific cost (i.e. the capital cost per kg of hydrogen dispensed) by 75%. Larger capacity stations of up to a few 1 000 kgH2/day are being planned, especially for heavy-duty applications, and these offer potential for further economies of scale. There is also potential for costs to be reduced through a shift to more advanced supply options (such as very high pressure or liquid hydrogen) and through scale-up in the manufacturing of refueling station products (via mass production of components, such as the compressors). (IEA, 2019)

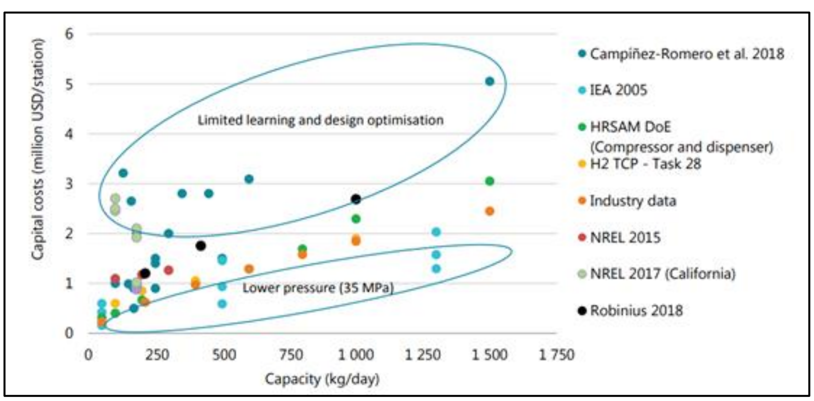


Figure 2.5.e Benchmarking hydrogen refueling station capital costs as a function of capacity

The costs of providing hydrogen to FCEVs can be brought down by building larger refueling stations as long as expected hydrogen demand allows as shown in Figure 7.4. Thus, there will be scale effects in deployment of hydrogen refueling stations.

Risks related to the tension between refueling station size, the cost of hydrogen and hydrogen demand are among the barriers to rapid hydrogen uptake for transport. Small stations make more economic sense in the initial deployment phase as they are more likely to secure higher capacity utilization rates when demand for hydrogen from transport vehicles is limited, but they come at higher cost per unit of hydrogen delivered. Once sufficient demand volumes have been established, larger stations become more economic and can help reduce the cost of hydrogen for the end users. The cost of delivered hydrogen will also depend on whether the hydrogen is produced locally or delivered from centralized production facilities. (2012) The cost advantages of centralized production may be outweighed by the cost of distribution to the refueling station by truck or pipeline. The cheapest option will be determined case by case.

2.5.3 Candidate locations for HRS

In real-world HRS planning, the candidate locations for HRS can be selected from all of the nodes on the network. It is also important to exclude locations that are impractical because of land use policies, land cost or the lack of suitable parcels of land.

Intuitively, candidate locations can be the current gas station sites, which can be further down selected by removal of sites that are impossible to add or be replaced by HRS equipment. Other types of candidate locations are population centers, highway entrances, inter-city long-distance trip stops, locations near early FCV drivers (Melaina, 2003).

2.5.4 Global status of hydrogen refueling stations and plans

The number of hydrogen refueling stations in the world is a rapidly increasing moving target. Nearly all are supported by government subsidies, typically on the order of a 50% cost share. The Pacific Northwest National Laboratory (PNNL, 2020) and National Renewable Energy Laboratory (AFDC, 2020) reports a total of 385 active hydrogen stations, with another 167 planned to open in the next year or two. Of the 385 active stations identified by PNNL, 268 (78.4%) are open to the public.

The capacity of many stations is not available in the H2 Tools database, yet stations dispensing hydrogen at 70 MPa or both 70 and 35 MPa comprise the large majority. The international standard for on-board storage for passenger cars is 70 MPa, while buses are frequently designed to store hydrogen at 35 MPa. Considering all stations in the PNNL database (active, planned, public and private) for which delivery pressure is available, 15.5% supply at 35 MPa only, 71.1% at 70 MPa only, and 13.4% can deliver hydrogen into a vehicle at either pressure (Fig. 2.5.f).

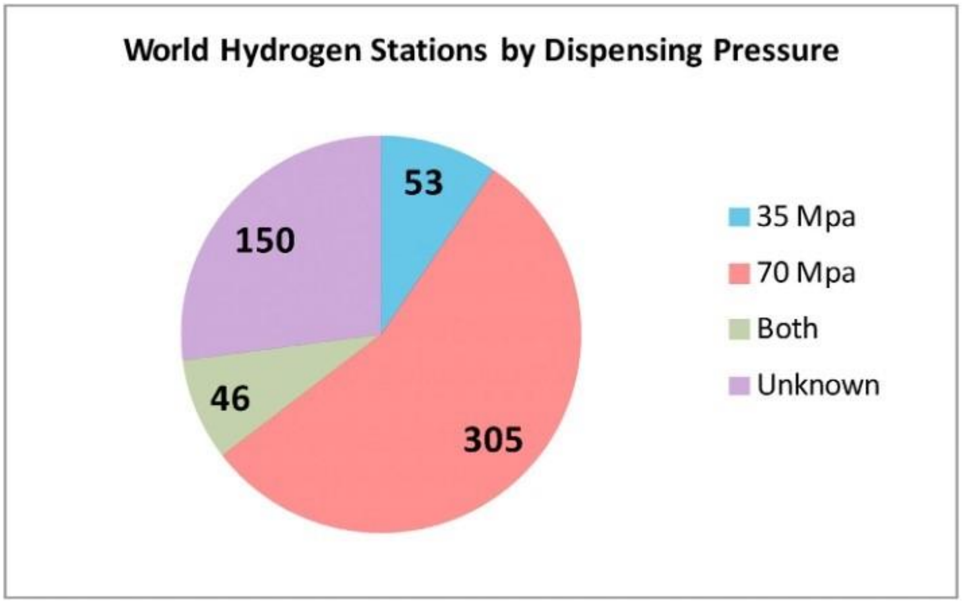


Figure 2.5.f World hydrogen stations by dispensing pressure (H2 tools, 2020)

The seven countries with the most hydrogen stations account for 82.3% of the active stations. The distribution of stations by the seven countries and the rest of the World, by status (public and private, active and planned) are shown in Fig. 7.6. Planned stations are typically expected to be opened within the current year. Four fifths of the stations are open to the public while others are for the use of bus companies or otherwise restricted.

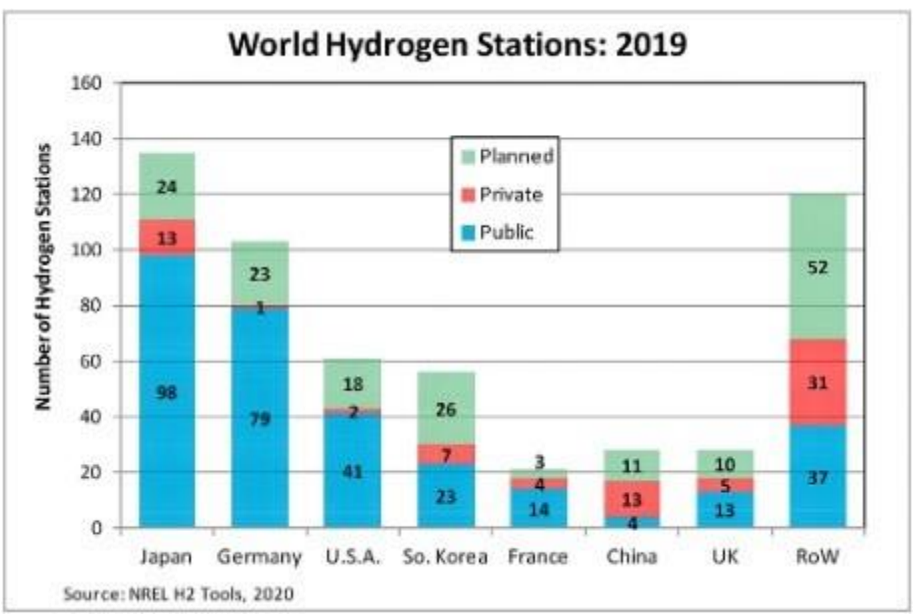


Figure 2.5.g World hydrogen stations (H2 tools, 2020)

2.5.5 Probable strategy

For low market penetration which might highly possible our current situation.

Ogden and Nicholas (2011) developed a station "cluster strategy" for deploying hydrogen refueling stations that was adopted by the State of California (CAFCP, 2012) [19-21]. The cluster strategy creates strategic niche markets for FCVs by locating several stations in smaller geographical areas with a high concentration of likely early adopters of FCVs. The geographical niches not only provide convenient and reliable access to subsidized stations but by spatially concentrating the adoption of a novel technology they accelerate diffusion by facilitating institutional and social learning. Concentrating demand creates the potential for station profitability at low levels of FCV market penetration.

The success of the cluster strategy is based on a more complex understanding of the need for stations in the early transition. Whereas prior studies estimated that the minimum number of hydrogen stations for creation of a mass market was 15%-20% of that of existing gasoline stations, the cluster strategy recognized that an individual FCV could accomplish more than 90% of a conventional vehicle's annual travel if only one station were located within a few kilometers of its home base. For example, well over 90% of the annual miles of travel of a typical household vehicle in California occur on days on which vehicle travel is well within the range of a FCV (Figure 2.5.h). In accord with this observation, a survey of FCVs in California found that they averaged 12,500 miles per year, 91% of the state average of 13,739 for 1-4-year-old conventional vehicles.

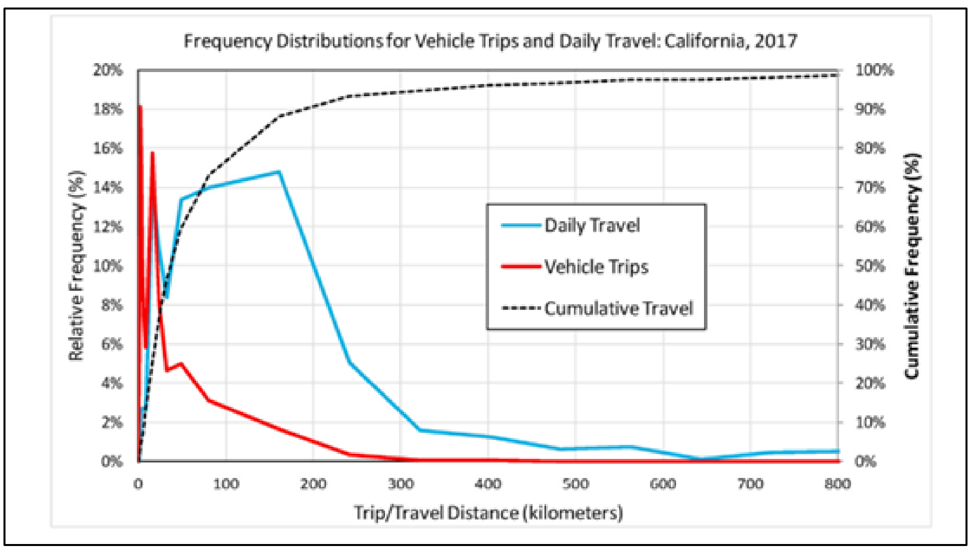


Figure 2.5.h Frequency distributions for vehicle trips

2.5.6 Modeling of deployment of refueling stations in Ithaca

Modeling by using data for Ithaca through Hydrogen Delivery Scenario Analysis Model

Market penetration is assumed to be 5%

By using gas hydrogen with 4 refueling stations (capacity: 1000 kg/day, 700bar)

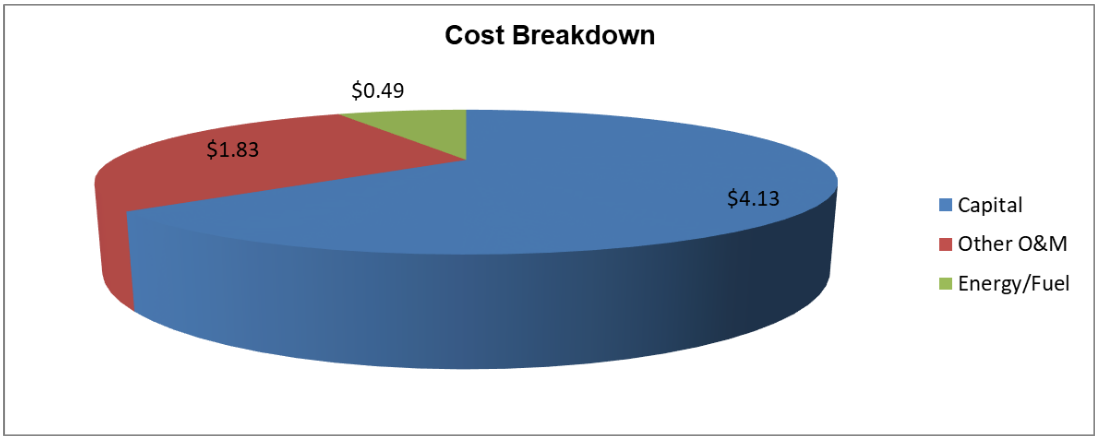


Figure 2.5.i Cost breakdown of gas refueling station

Table 2.5.a Cost breakdown of gas refueling station

Cost Breakdown					
	GH2 Terminal [$/kg]	**Geologic Storage [$/kg]**	**Compressed H2 Truck-Tube [$/kg]**	**Gaseous Refueling Station [$/kg]**	**Sum [$/kg]**
Total Cost [$/kg]	$1.8160	$0.4810	$1.6581	$2.4988	$6.4538
Capital	$0.9713	$0.2059	$1.3221	$1.6356	$4.1349
Other O&M	$0.6363	$0.2743	$0.2482	$0.6687	$1.8274
Energy/Fuel	$0.2084	$0.0008	$0.0878	$0.1945	$0.4914

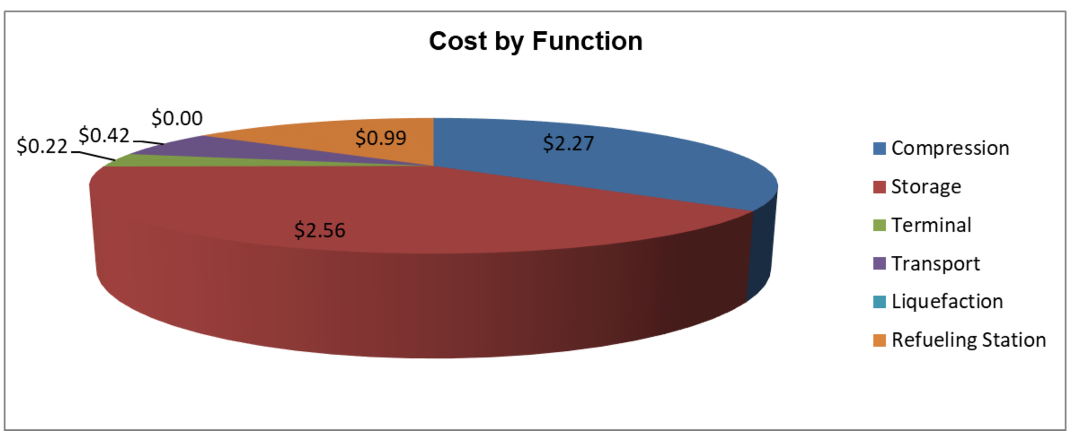


Figure 2.5.j Cost by function of gas refueling station

Table 2.5.b Cost by function of gas refueling station

Cost by Function $/kg						
	Compression	**Storage**	**Terminal**	**Transport**	**Liquefaction**	**Refueling Station**
Capital	$1.2475	$2.0643	$0.1206	$0.0942	$0.0000	$0.6083
Other O&M	$0.6918	$0.4911	$0.0994	$0.2334	$0.0000	$0.3118
Energy/Fuel	$0.3355	$0.0000	$0.0000	$0.0878	$0.0000	$0.0682
Total Cost [$/kg]	$2.2748	$2.5554	$0.2200	$0.4154	$0.0000	$0.9882

Table 2.5.c Annual Cost and Energy Breakdown, and Land Area of gas refueling station

Annual Cost and Energy Breakdown, and Land Area						
	Total Capital Investment	**Standard O&M (Less energy cost)**	**Electrical Energy Consumption (MJ)**	**Truck Fuel Consumption (MJ)**	**GH2 Terminal Land Area (m^2)**	**GH2 Refueling Station Land Area (m^2)**
	$16,121,898	$1,037,404	9,476,624	2,574,372	5,236	997

The total unit cost by using gas hydrogen with 1000 kg/day, 700bar refueling station is about $6.45/kg. The capital cost occupies the largest fraction and can be decreased with larger market penetration. By using liquified hydrogen with 2 refueling stations (capacity: 1600 kg/day, 700bar)

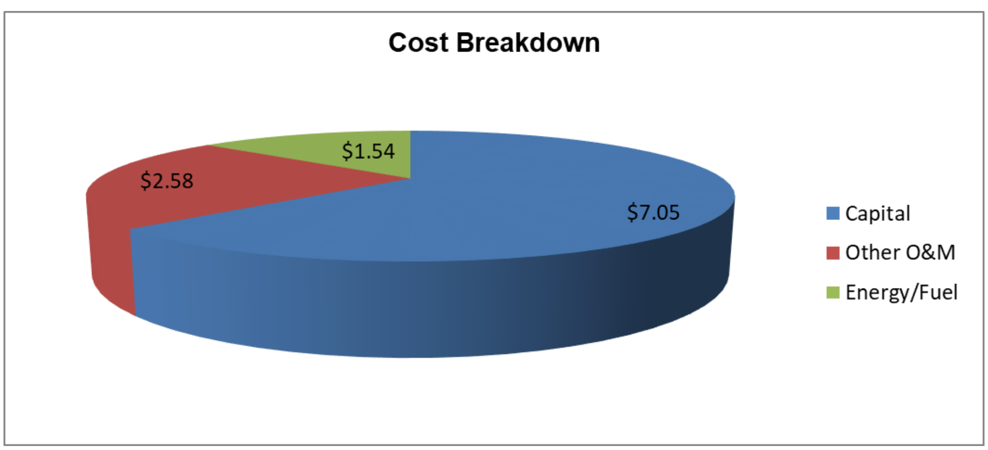


Figure 2.5.k Cost breakdown of liquid refueling station

Table 2.5.d Cost breakdown of liquid refueling station

Cost Breakdown					
	Liquefier [$/kg]	Terminal [$/kg]	Tractor-Trailer [$/kg]	Liquid Refueling Station [$/kg]	Sum [$/kg]
Total Cost [$/kg]	$4.92	$2.33	$0.54	$3.39	$11.18
Capital	$2.89	$1.63	$0.45	$2.09	$7.05
Other O&M	$0.97	$0.70	$0.08	$0.83	$2.58
Energy/Fuel	$1.06	$0.00	$0.02	$0.47	$1.54

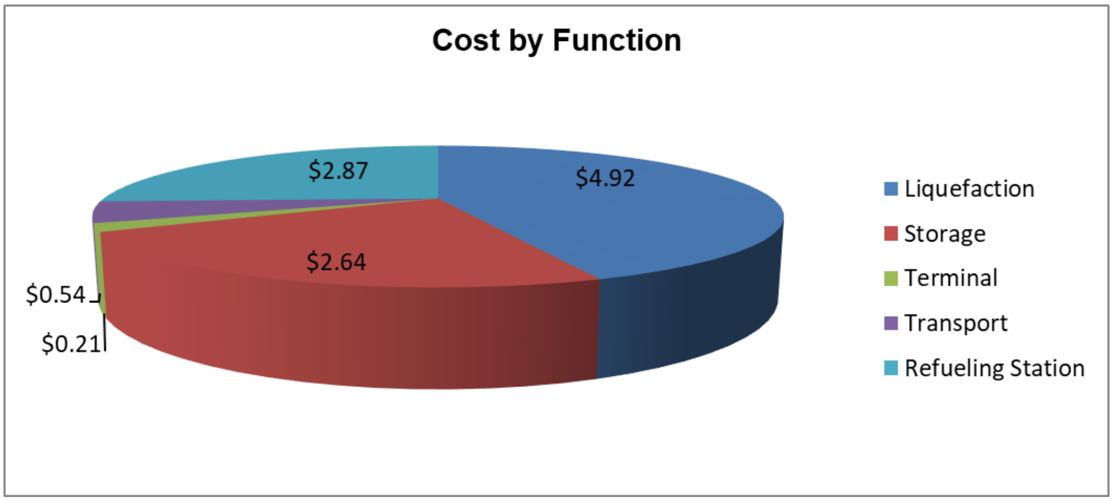


Figure 2.5.m Cost by function of liquid refueling station

Table 2.5.e Cost by function of liquid refueling station

Cost by Function $/kg					
	Liquefaction	Storage	Terminal	Transport	Refueling Station
Capital	$2.89	$1.89	$0.14	$0.45	$1.68
Other O&M	$0.97	$0.76	$0.00	$0.08	$0.72
Energy/Fuel	$1.06	$0.00	$0.06	$0.02	$0.47
Total Cost [$/kg]	$4.92	$2.64	$0.21	$0.54	$2.87

Table 2.5.f Annual Cost and Energy Breakdown, and Land Area of liquid refueling station

Annual Cost and Energy Breakdown, and Land Area						
	Total Capital Investment	**Standard O&M (less energy cost)**	**Electrical Energy Consumption (MJ)**	**Truck Fuel Consumption (MJ)**	**LH2 Terminal Land Area (m^2)**	**LH2 Refueling Station Land Area (m^2)**
	$29,194,623	$1,668,495	42,039,216	490,143	7,346	2,513

The total unit cost by using gas hydrogen with 1600 kg/day, 700bar refueling station is about $11.8/kg. It is higher than that of gas hydrogen refueling station because of the high cost of liquification. The capital cost still occupies the largest fraction.

4. Hydrogen transportation

4.1 Comparison of delivery cost of truck and pipeline

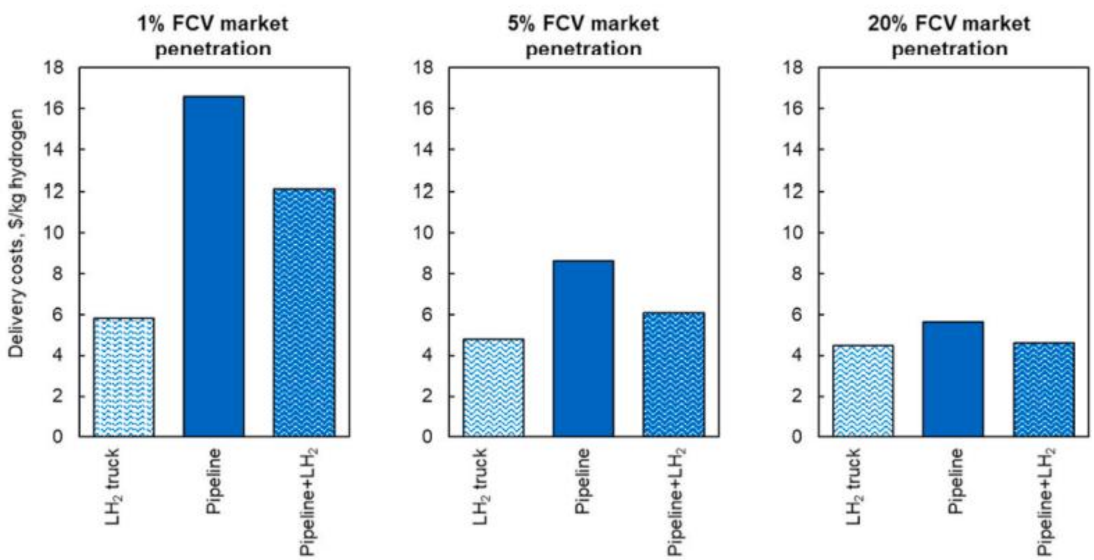


Fig.4.1 Effect of market penetration on cost of different transportation methods

Market penetration will significantly affect the cost performance of using pipeline to distribute hydrogen. When the market penetration is over 20%, the unit delivery cost of hydrogen by using pipeline will have advantage over using trucks. This critical value will be affected by some factors like the number of local vehicles, but generally, when the usage of hydrogen fuel cell vehicle is still in the early stage, using pipeline as the delivery method is not recommended. The delivery cost estimation result by using Hydrogen delivery scenario analysis model with data in Ithaca is similar to this trend.

4.2 Comparison of liquid and gas hydrogen

Table 1. Comparison of deliverable amount of energy with a standard 40 to truck (26 to/maximum 45 m3)

	Compressed 200 bar	Liquid	Liquid/slush	Gasoline
Density (kg m^{-3})	20	70.79	85	720–770
Stored mass (kg)	350	2100–4000	2450	26 000
Stored energy	14.5 GJ	300–572 GJ	420 GJ	1144 GJ

There are many ways to storage hydrogen such as using hydrogen gas or liquid or Metal Hydride. According to this table, the energy density of using hydrogen gas is quite low and not suitable for long distance transportation. For a distance of 100 km energy consumption of 1.8 GJ has to be taken into account. The typical energy demand of the installed units for hydrogen liquefaction is between 36 and 54 MJ/kg. The ideal work of liquefaction of hydrogen is 11.62 MJ/kg. The goal for future efficiency-optimized installations should be 25 MJ/kg for hydrogen. If the liquified hydrogen is decided to be used, the energy consumption of liquification and the relevant equipment cost should also be taken into consideration. [2-3]

There will be further discussion about cost variance between gas and liquid hydrogen in the chapter of deployment of refueling stations.

3. Solar Harvesting

Solar harvesting the is the process of capturing and subsequently storing the solar energy from the sun. There are various factors like the location of the solar farm, type of solar panels, tilt angle to the panels, etc. that come into play when proposing an energy efficient solar farm. In the section below, we are going to discuss about the availability of sunlight in Ithaca region. Further, we will be calculating the amount of electricity generated and finally estimate the cost of the entire project.

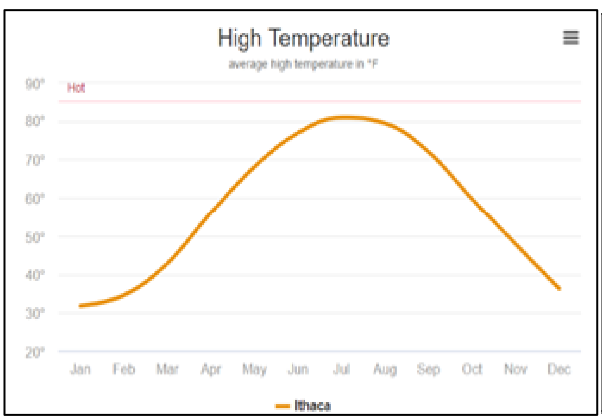
3.1. Solar energy availability in Ithaca

Ithaca is located in the upstate New York. The location experiences heavy snowfall in during the winter months which usually starts from December and lasts till March. The average number of sunny days in Ithaca are 155 days which is less than the national average of 205 days. (https://www.bestplaces.net/climate/city/new_york/ithaca)

We believe that we can capture maximum sunlight during the sunny days. However, there are several environmental factors that affect the efficiency of the solar panels.

<u>Effect of heat on Solar Panel efficiency:</u>

When the atmospheric conditions are too hot, solar panels do not generate as much power as when the weather is cooler. It is therefore quite normal for solar systems to generate less electricity on a hot day, and more on a cool or windy day. (http://solar365.com/solar/photovoltaic/how-temperature-affects-solar-panels)



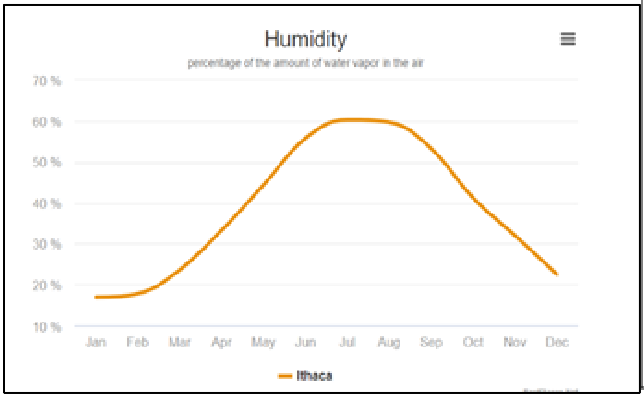
The graph on the left shows how the temperature changes in Ithaca. July being the hottest month, we believe that the solar panel efficiency would be comparatively less.

However, it has been observed that during the high temperature months the duration of sunlight is more which compensates for the lost efficiency.

Figure 3.1.a High temperature graph in Ithaca

<u>Effect of humidity on Solar Panel efficiency:</u>

Experimentally it has been observed that as the humidity increases the voltage, current, and the Power (watts) decreases.



After the experiments conducted, humidity drastically effects the performance of the Solar Panel and proves out to decrease the Power produced from the Solar Panels up to 15-30% if subjected to environment where in the Humidity level remains high

Figure 3.1.b Humidity curve in Ithaca

3.2. Solar energy calculations

For the purposes of this project, we assume that it is feasible to build a solar farm around Ithaca to reduce transmission costs while powering the project's equipment.

On October 7, in a meeting of hydrogen stakeholders, Ryan McCune from Next Amp, Incorporated, a commercial solar PV installer, stated that their company had estimated the capacity on the roof of Chain works to be 1 MW of capacity. (McCune, R,2021, Personal communication)

Our team decided to build a new 3MW solar power station that would be able to power the system. The result is that we have a total of 4MW solar power stations.

For our calculations, we are going to use PVWatts – NREL software to calculate the amount of electricity that we can generate in the Ithaca region based on different input parameters. In this section, we are going to first discuss different input parameters and how they affect our solar energy generation. Second, we calculate the annual output and the area we need.

3.2.1 Input parameters

a. Location input: The latitude and longitude of the location helps us determine the amount of sunlight that falls in a particular location.

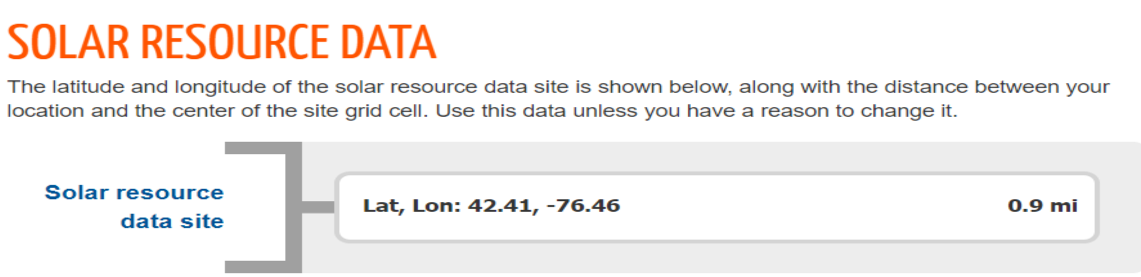


Fig.3.2.a Location data site of Ithaca （PVWatts® Calculator）

b. Type of Solar panel

Major types of solar panels

SOLAR PANEL TYPE	ADVANTAGES	DISADVANTAGES
Monocrystalline	High efficiency and performance	Higher costs
Polycrystalline	Lower costs	Lower efficiency and performance
Thin-film	Portable and flexible	Lower efficiency and performance

Fig. 3.2.b Solar panel type（Marsh, J. 2021）

Among all panel types, monocrystalline panels generally have the highest efficiency and power capacity. The efficiency of monocrystalline solar panels can reach more than 20%, while the efficiency of polycrystalline solar panels is usually between 15% and 17%. **(Marsh, J. 2021**）

Our team decided to use Monocrystalline solar panels, which in the PVWatts system corresponds to a module type is Premium, and its Approximate Nominal Efficiency is 19%.

c. Array type

To take full advantage of solar panels, we need to point them in the direction that captures the most sunlight. But there are many variables in determining the best direction.

The easiest way to install the solar panels is that install the panel on a fixed tilt and leave them there. But because the sun is higher in summer and lowers in winter, we can adjust the tilt of the solar panel according to the season to get more energy throughout the year. The tracking system is more complicated than the fixed system, and the maintenance cost is too expensive. We do not consider this system in our project.

The table and graph below use a system with a latitude of 40° as an example to show the effect of adjusting the angle. It has also compared their differences with the 2-axis system.

	Fixed	Adj. 2 seasons	Adj. 4 seasons	2-axis tracker
% of optimum	71.1%	75.2%	75.7%	100%

Table 3.2.c Optimum angle table

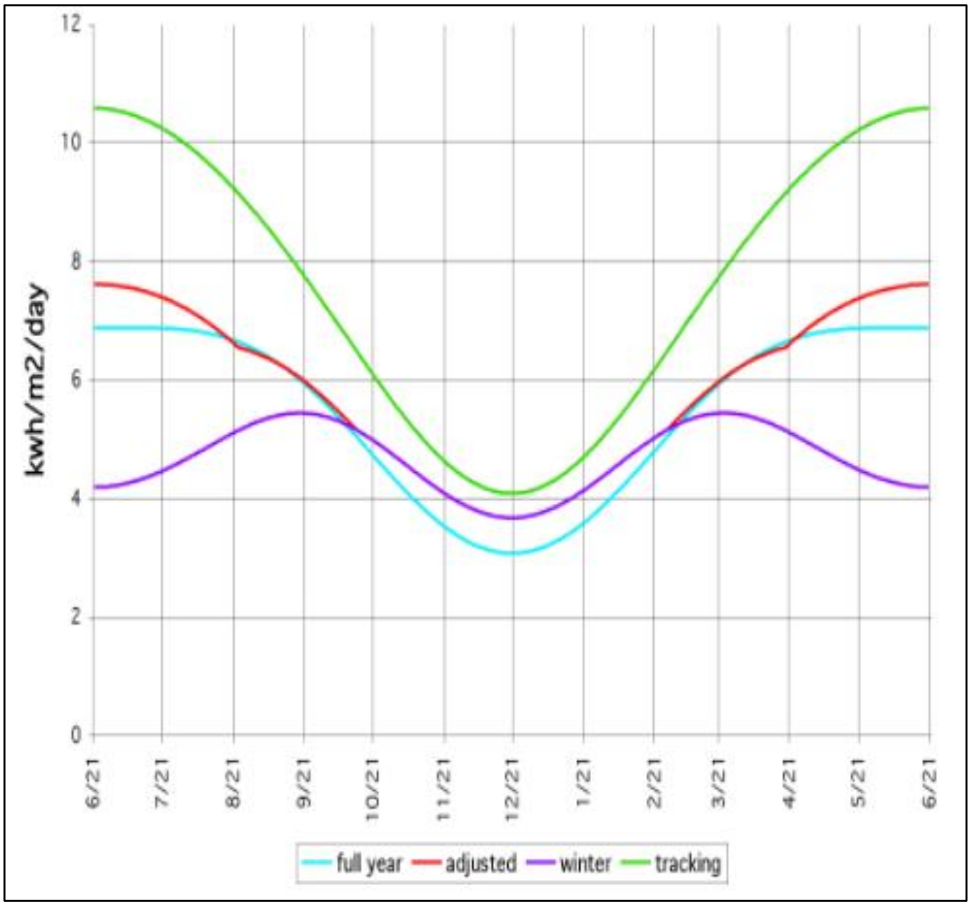


Fig. 3.2.c Effect of adjusting the angle (Landau,2017)

It can be clearly seen that adjusting the tilt twice or 4 times a year only gives us a slight increase in energy output. Adjusting the tilt angle of the system requires a manual adjustment fee, which is more suitable for solar systems in small residential areas, and for utility-scale solar systems, they are more suitable for fixed systems.

The fixed open rack arrays are suitable for ground-mounted systems. This system assumes that air flows freely around the array, helping to cool the module and lower the operating temperature of the battery. Under a given incident solar irradiance, the output of the array increases as the temperature of the battery decreases.

In summary, we have chosen a fixed system.

d. Tilt angle

The latitude of Ithaca is 42.41, this number falls in range 25° - 50°. If the latitude is between 25° and 50°, then the best tilt angle for full year is the latitude, times 0.76, plus 3.1 degrees. **(Landau,2017)**

Tilt degree: 42.41*0.76+3.1= 35.3316

Table 3.2.b Tilt angle results

3MW New station	35.3316
1MW Roof Top Station	35.3316

e. Azimuth angle

For locations in the northern hemisphere, the default azimuth is 180° (towards south), and for locations in the southern hemisphere, the default azimuth is 0° (towards north). These values usually maximize electricity production within a year. （PVWatts , NREL)

f. System Losses:

Use the default value of PVWATTS, 14.08. The parameters that affect System Losses are listed in the diagram below.

Default values for the system loss categories	
Category	**Default Value (%)**
Soiling	2
Shading	3
Snow	0
Mismatch	2
Wiring	2
Connections	0.5
Light-Induced Degradation	1.5
Nameplate Rating	1
Age	0
Availability	3

Fig. 3.2.d Default values factors （PVWatts , NREL)

g. Input Facotrs

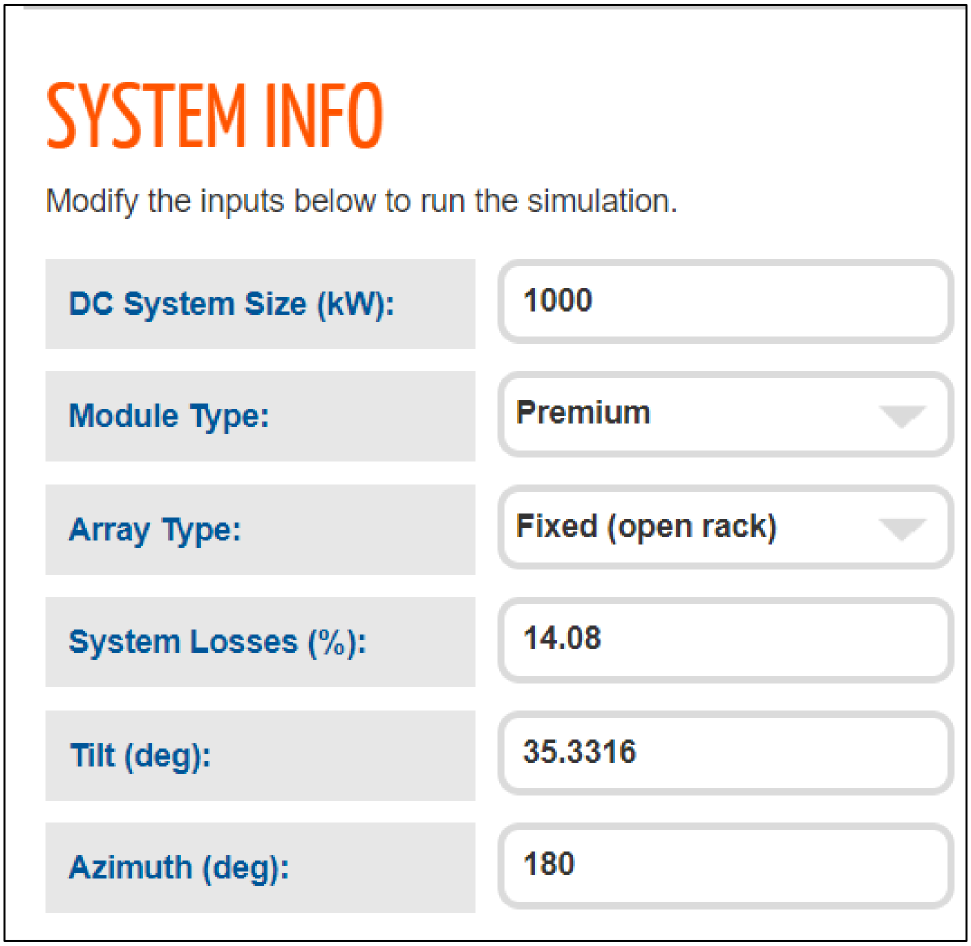


Fig. 3.2.e. Input panel （PVWatts , NREL)

3.2.2 Output and Area requirements

a. Annual output

In order to obtain the maximum energy output, it is most appropriate to adjust the angle of the solar panels to 35.3316 degree. We calculate the energy output for two solar panel systems. The energy output of each part of the system will be calculated through the PVWATTS software, and then adds them together to get the maximum energy output we need.

RESULTS

Print Results

3,738,466 kWh/Year*

System output may range from 3,599,021 to 3,853,984 kWh per year near this location.
Click HERE for more information.

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)	Value ($)
January	2.71	211,552	19,547
February	3.76	261,322	24,146
March	4.52	340,173	31,432
April	5.33	372,184	34,390
May	5.69	398,990	36,867
June	5.58	377,431	34,875
July	5.93	403,739	37,306
August	5.68	389,109	35,954
September	5.05	341,364	31,542
October	3.65	265,038	24,489
November	2.81	204,568	18,902
December	2.23	172,994	15,985
Annual	4.41	3,738,464	$ 345,435

Fig. 3.2.f. 3MW system summertime Energy results （PVWatts , NREL)

RESULTS

Print Results

1,246,155 kWh/Year*

System output may range from 1,199,674 to 1,284,661 kWh per year near this location.
Click HERE for more information.

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)	Value ($)
January	2.71	70,517	6,516
February	3.76	87,107	8,049
March	4.52	113,391	10,477
April	5.33	124,061	11,463
May	5.69	132,997	12,289
June	5.58	125,811	11,625
July	5.93	134,580	12,435
August	5.68	129,703	11,985
September	5.05	113,788	10,514
October	3.65	88,346	8,163
November	2.81	68,189	6,301
December	2.23	57,665	5,328
Annual	4.41	1,246,155	$ 115,145

Fig. 3.2.g 1MW System Energy results （PVWatts , NREL)

Table. 3.2.c Annul energy output

3MW New station	**3,738,466 kwh**
1MW Roof Top Station	**1,246,155 kwh**
Total	**4,984,621 kwh/year**

b. Area requirements

CGCG considered that 80% of the Chainwork's roof area is available for installing the solar panels, which equates to approximately 320,000 ft2. (Cornell green consulting group,2011)

The table below comes from an NREL report about land use of solar plants in the United States. The report identifies two significant solar plant land use classes: direct impact (disturbed land due to physical infrastructure development) and total area (all land enclosed by the site boundary). We can use this table to find the size we need for a new solar firm.

Table. 3.2.d Area requirements (Ong, S, 2013).

Table 8. Summary of Direct Land-Use Requirements for PV and CSP Projects in the United States

Technology	Direct Area					
	Number of projects analyzed	Capacity for analyzed projects (MWac)	Capacity-weighted average land use (acres/MWac)	Capacity-weighted average land use (MWac/km^2)	Generation-weighted average land use (acres/GWh/yr)	Generation-weighted average land use (GWh/yr/km^2)
Small PV (>1 MW, <20 MW)	92	374	5.9	42	3.1	81
Fixed	43	194	5.5	45	3.2	76
1-axis	41	168	6.3	39	2.9	86
2-axis flat panel	4	5	9.4	26	4.1	60
2-axis CPV	4	7	6.9	36	2.3	105
Large PV (>20 MW)	15	1,405	7.2	34	3.1	80
Fixed	7	744	5.8	43	2.8	88
1-axis	7	630	9.0	28	3.5	71
2-axis CPV	1	31	6.1	41	2.0	126
CSP	18	2,218	7.7	32	2.7	92
Parabolic trough	7	851	6.2	40	2.5	97
Tower	9	1,358	8.9	28	2.8	87
Dish Stirling	1	2	2.8	88	1.5	164
Linear Fresnel	1	8	2.0	124	1.7	145

Table. 3.2.e2 Area requirements

Fixed system capacity (Roof Station)	**1MW**
Total area (ft^2) (Roof Station)	**320,000(ft^2)**

Fixed system capacity (New Station)	**3MW**
Land-Use Requirements	**45MWac/km^2**
Total area (ft^2) (New Station)	**721182 (ft^2)**
Total area (ft^2)	**1041182 (ft^2)**

3.3. Estimated cost of setting up Solar panels

The installation cost of a solar power plant is usually between US$0.82 and US$1.36 per watt. This means that a 1-megawatt solar power plant will cost US$820,000 to US$1.36 million. (Hyder, 2019)

We used the SEIA table, which listed the average cost of the United States in the first quarter of 2020. For the construction of solar farms, the utility-scale system is cheaper than the rooftop solar system, which is generally half of the residential solar cost.

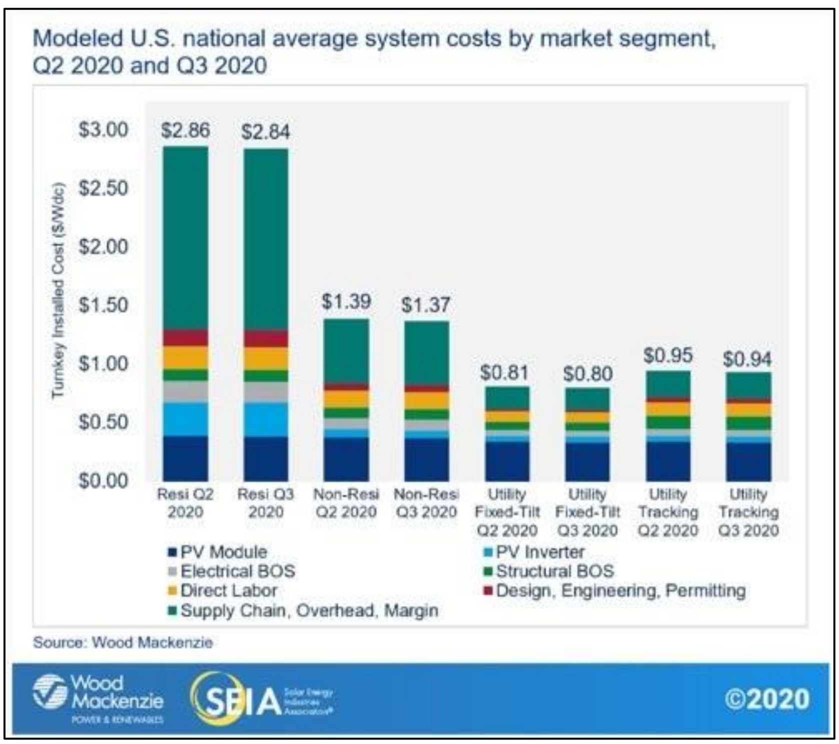


Fig.3.3.a Average System Costs (Hyder, 2019)

By using utilit fixed-tilt Q3 2020 index we obtain the table below

Table. 3.3.a Total costs

3MW New station	**$ 2.4 Million**
1MW Roof Top Station	**$ 0.8 Million**
Total	**$ 3.2Million**

4. Wind Harvesting

4.1. Wind energy availability near Ithaca

Wind energy can also provide power for electrolysis to produce hydrogen. Wind energy was chosen to produce power for electrolysis because it is also a renewable source of electricity. Another reason for this choice is due to the characteristics of wind production. Wind production typically compliments the production of solar production on both a seasonal and diurnal basis. Wind farms typically produce more over the winter months and at night while solar produces more during the summer months and during the day. Figures 4.1.a and 4.1.b show seasonal variation in solar and wind production from various locations in the U.S. (Vanek, et. al., 2012). Additionally, figure 4.1.c shows the diurnal complementing of wind and solar resources in the Ithaca area (Vanek, et. al., 2012). Having both wind and solar resources diversifies the portfolio of renewable energy powering hydrogen production. Having multiple resources increases reliability and provides a less volatile source of electricity to power electrolysis.

Fig. 4.1.a Seasonal variation in solar production by location.

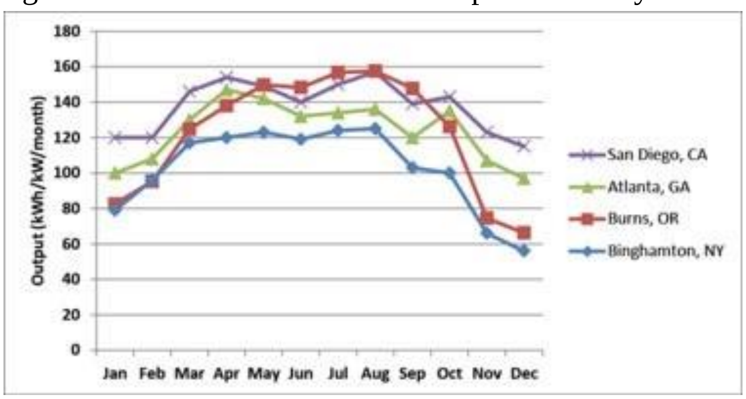


Fig. 4.1.b Seasonal variation in wind production by location.

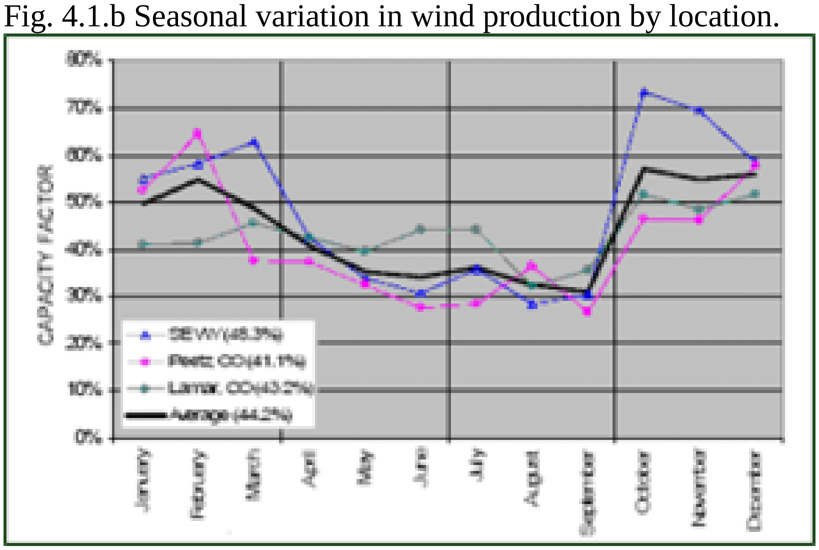
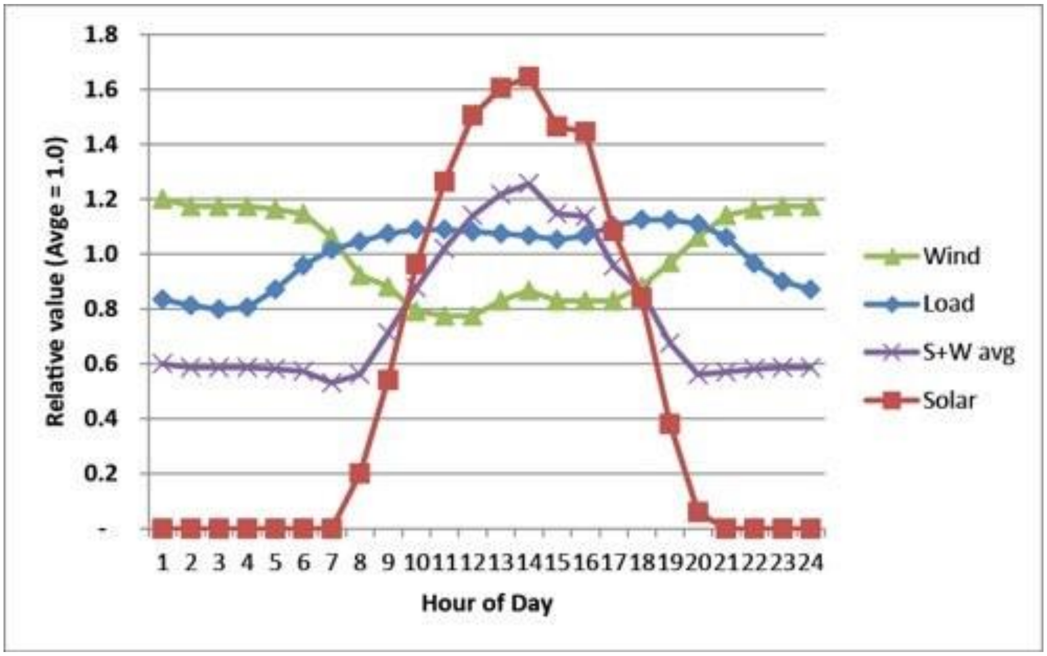
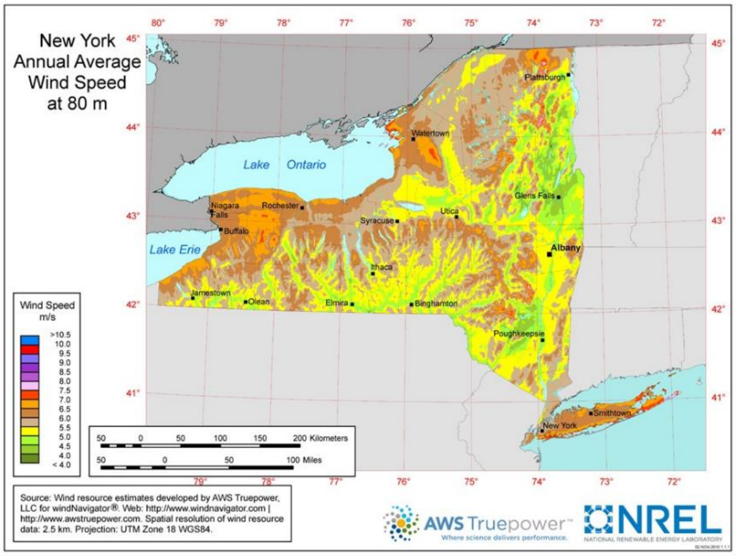


Fig. 4.1.c. Relative diurnal complementing of wind and solar resources with demand in Ithaca, NY.



Wind is a generally widely available resource, yet some locations are better suited for turbine installation than others. For the purposes of this project, it is assumed that locating a wind farm to install turbines would be feasible in the state of New York. Locating turbines in the state of New York is a choice made to reduce transmission losses over long distances. And, this decision also allows for a reasonable amount of flexibility for wind farm location to be installed in a preferred location based on wind availability. Fig 4.1.d shows wind availability at 80m in the state of New York (NREL, 2010).

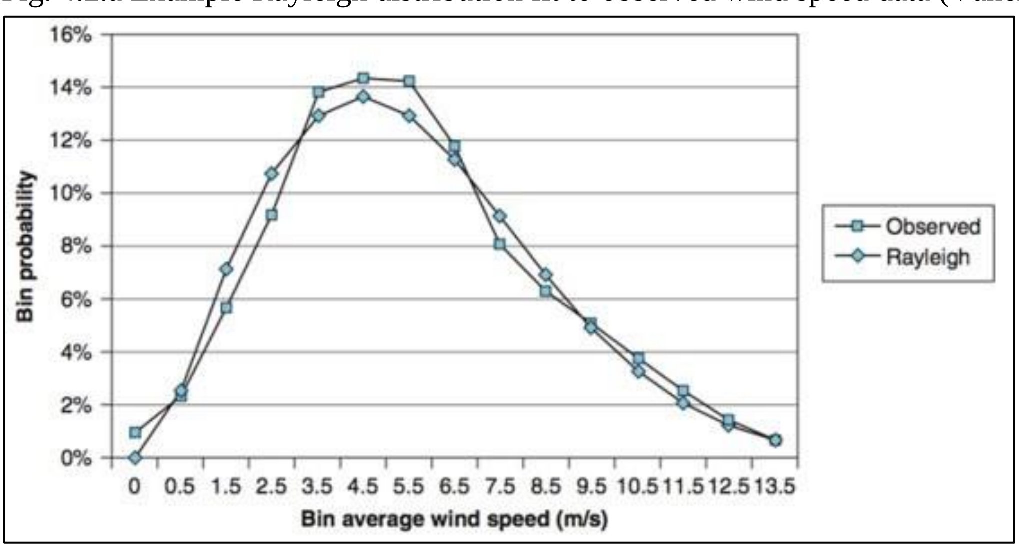
Fig. 4.1.d. New York Annual Average Wind Speed at 80m.



4.2. Wind energy calculations

For the purposes of this project, it is assumed that 1.7 MW horizontal axis wind turbines can be installed around the state of New York with a hub height of 100m. The output of a proposed turbine can be estimated using a Rayleigh distribution of wind speed at the hub height given an average annual wind speed at a specified location. A Rayleigh distribution returns a probability of an outcome characterized by the equation F(U)=1-exp(-(pi/4)*(U/U-avg)^2) where U is the wind speed and U-avg is the average annual wind speed (Vanek, et. al., 2012). The cumulative distribution function can be separated into bins, categories defined by a low and high criterion based on wind speed, U. Fig 4.2.a below shows an example of a cumulative distribution function using a Rayleigh function fit to observed wind speed data.

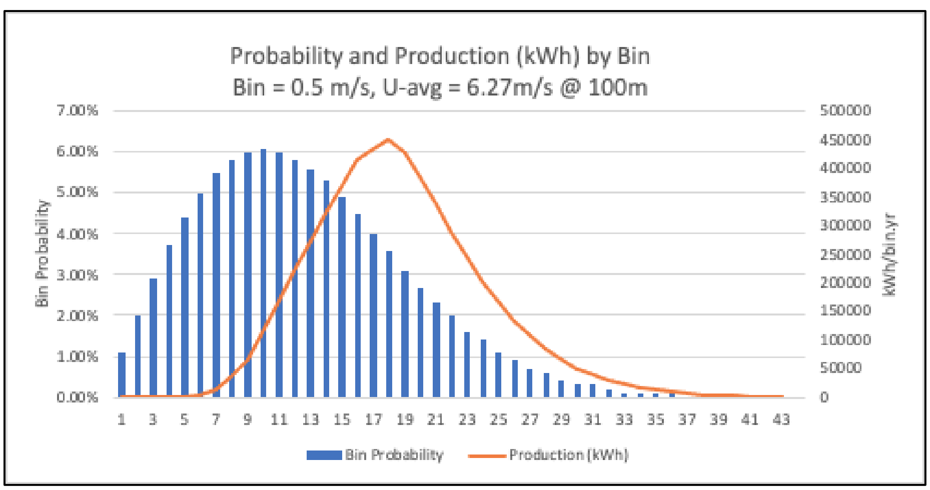
Fig. 4.2.a Example Rayleigh distribution fit to observed wind speed data (Vanek, et. al., 2012).



The annual power output of a turbine was calculated as follows. The bin size was defined as 0.5 m/s with the bin center on 0.5 m/s increments. Ex. Bin 5 represents the probability the wind speed will be from 2.75-3.25 m/s. Bin 5's center is 3.0 m/s. The probability of the wind speed occurring within the bin limits can be found using the Rayleigh distribution to find the probability of the bin's maximum wind speed and then subtracting the probability of the bin's minimum wind speed. Multiplying the bin probability by the number of hours in a year gives the predicted number of hours per year the wind is blowing in the bin speed. Vanek, et. al. gives a power curve for a 1.7 MW turbine. The power curve represents the output of a 1.7 MW turbine given a certain wind speed. Multiplying the power output of the turbine by the number of hours of each bin yields an annual production in kWh for each bin. Summing the annual production of each bin then yields an estimated total annual production for a single 1.7 MW turbine predicted from the average annual wind speed. The calculations for this estimation along with the power curve can be fully seen in Appendix A. The power curve used for the 1.7 MW turbine holds characteristics of turbine operation. Notably, the turbine does not produce energy below a wind speed of 2.75 m/s nor above 21.75 m/s representing that wind power cannot be harnessed at low wind speeds nor above the rated limits of a turbine.

For this calculation, an average annual wind speed of 6.0 m/s was chosen from Fig 4.1.d as a reasonable, yet favorable site selection for wind turbine location in New York. This value of 6.0 m/s is given at 80 m and was adjusted for a 100 m hub height using the wind speed height adjustment equation outline by Vanek, et. al. This equation adjusts the reference height (z-r) to a target height (z) using a typical scaling factor (alpha) of 0.2 in the equation z = z-r * (U(z)/(U(z-r))^(1/0.2) where U(z) is the wind speed at the target height and U(z-r) is the wind speed at the reference height. The adjusted wind speed at 100 m was 6.27 m/s, which corresponds to a chosen annual average wind speed of 6.0 m/s at 80 m. Below in figure 4.2.b is the graphical output of the production estimates by bin using a Rayleigh distribution, highlighted by the orange line.

Fig 4.2.b Probability and annual production by bin from 6.27 m/s average annual wind speed at 100 m.



Summing the production in each bin yields a total estimated production of 5.51 million kWh per year. If the wind turbine can take advantage of all the production each year, meaning there is no downtime when the wind is blowing within the operating range, the capacity factor of a 1.7 MW turbine in this scenario is 37.0%. A wind farm that would suit the applications for this project best would be a wind farm consisting of many 1.7 MW turbines. A more realistic capacity factor may be lower than 37% to account for down-time, repairs, and maintenance.

For comparison, the Fenner Wind Farm, located southeast of Syracuse, NY sits between the 5.5 and 6.5 m/s area on the NREL 80m wind speed map. This location should have roughly the availability of the proposed 6.0 m/s wind farm for this project. In email correspondence with the local wind farm in 2004, Vanek found that the Fenner Wind Farm has a capacity factor of 32.3 percent. This lower capacity factor could also be due to the smaller turbine size of 1.5 MW and the older technology of the turbines at Fenner, having been constructed in 2000.

It is unusual for wind turbines to be installed on a solitary basis. Typically, multiple wind turbines are installed together on a wind farm to share costs of grid connection and substation support. It is assumed that the installation of the turbine needed for this project could be purchased or built as part of a larger development project to offset the costs of permitting and grid connection.

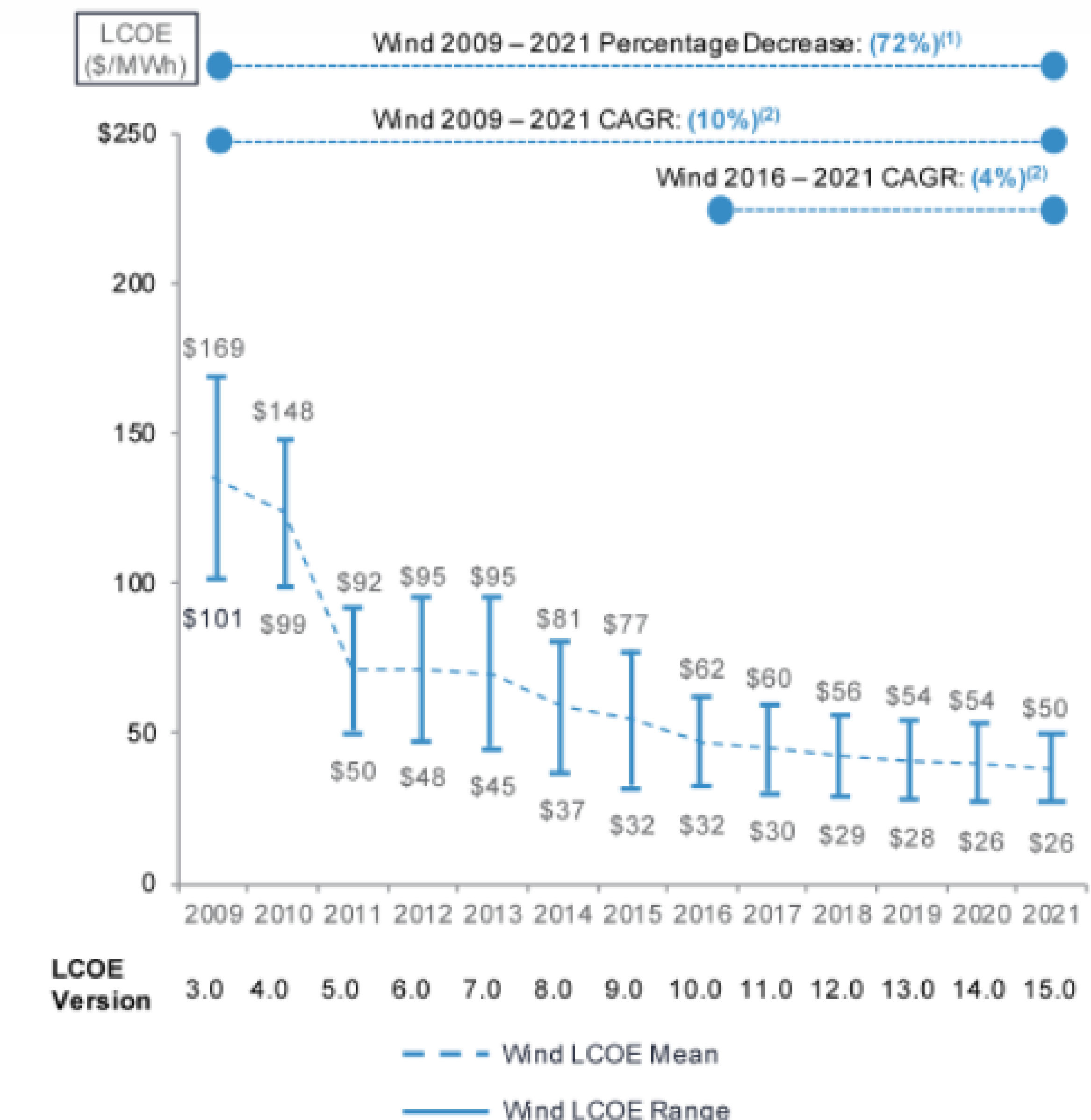
4.3. Estimated cost of setting up wind turbines.

The cost of wind energy is dependent on the quality of the resource available. As the industry has gained significant traction and market share, the cost of wind energy has fallen significantly. Figure 4.3.a shows this decline in price over time (Lazard, 2021).

Figure 4.3.a. Unsubsidized Levelized Cost of Energy for Wind Production.

Lazard's levelized cost of energy model version 15.0 puts the cost of wind between $26 and $50 per MWh. Subsidized, this LCOE can drop to $9-$40/MWh. Because of the selected location of the wind farm being sited in New York state, the LCOE for wind production in this project is likely to range on the higher end of this spectrum. Wind resources are more abundant and favorable across the continental West and Midwest as well as near shorelines. Given the 5.51 GWh/yr of production, the cost of this 1.7 MW installation ranges from $143390 to $276,000 per year. Subsidized, this cost ranges from $49635 to $220600 per year. It is likely the LCOE will lean towards the upper end reflecting the availability of wind resources in New York state. The cost will also be reflective of the incentives and financing options available, which is beyond the scope of this project.

Unsubsidized Wind LCOE



Source: *Lazard estimates.*

(1) Represents the average percentage decrease of the high end and low end of the LCOE range.

(2) Represents the average compounded annual rate of decline of the high end and low end of the LCOE range.

5. Electrolyzers:

5.1 The choices of electrolyzes:

While electrolysis makes up a small share of the hydrogen generation market, electrolysis holds the key to unlocking green hydrogen production. The technologies for water electrolysis which are presently considered viable include: Alkaline Electrolysis (AEL); Proton Exchange Membrane (PEM); and to a lesser extent Solid Oxide Electrolysis (SOEL) (Burton, et al., 2021).

Alkaline Electrolysis is the most mature electrolysis method and is characterized by low capital costs with flexibility to operate from 10%-100% rated capacity. Alkaline electrolysis has been used since the 1920s to produce fertilizer and chlorine but was replaced by cheaper hydrogen generation methods of SMR and in the 1970s (IEA, 2019).

Proton Exchange Membrane Electrolysis was developed in the 1960s, using only water as an electrolyte solution. This avoids the recycling of the potassium hydroxide electrolyte solution needed in AEL. PEM electrolysis relies on platinum and iridium, raising the capital cost of these systems. However, they are roughly twice as compact than their AEL counterparts, can operate from 0-160% of design capacity, and operate at higher pressures (IEA, 2019). This operation at higher pressures is particularly attractive as the energy required for liquefication of hydrogen is equivalent to 30% of the potential energy of the stored hydrogen (Burton, et al., 2021).

In addition to AEL and PEM, solid oxide electrolysis has seen attention in studies and the industry. Solid oxide electrolysis operates at high temperature, using steam for electrolysis. It employs ceramics for the electrolyte. SOEL has high electrical efficiencies and can be run in reverse, acting as a fuel cell. Waste heat can be used to generate steam needed for electrolysis. SOEL technology has yet to become commercially viable and suffers from high degradation of the electrolyzer because of such high operating temperatures (IEA, 2019)

Considering working conditions, efficiency, capital cost and serval external factors like the distributed station and unstable renewable energy input. Finally, we choose PEM electrolyzer for our project.

The main reason is PEM electrolyzer can work in a low temperature and has acceptable efficiency even in a small size that operate in our distributed station. And the PEM electrolyzer can start/stop quickly compare with SOEL. Besides, It can be reversible devices and are able to operate at lower cell voltages, higher current densities and pressures. But in the stakeholder presentation, we receive some pretty good suggestion to improve our design. Dr. Vanek and Dr. Anderson indicate we can purchase from grid. We already considered about this plan before but we finally drop it due to the emission

But the “ Community Choice Aggregation” provided by New York State Energy Research and Development Authority (NYSERDA) give us a different perspective to view our project and the choice of the electrolyzer.

Operational conditions	AEL	PEM	SOEL
Temperature (°C) [59,62,63]	40–90	20–100	650–1000
Pressure (bar) [59,64]	<30	<200	<20
Cell area (m^2) [59,64]	<4	<0.13	<0.06
Current density (Acm^{-2}) [59,62,63]	0.2–0.4	0.6–2.0	0.3–2.0
Voltage (V) [62,63]	1.8–2.4	1.8–2.2	0.7–1.5
Production (Nm^3/h) [59]	<1400	<400	<10
Gas purity (%) [64,65]	>99.5%	>99.99	>99.9
Stack energy consumption (kWh/Nm^3) [59,62,64]	4.2–5.9	4.2–5.5	>3
System energy consumption (kWh/Nm^3) [59,66]	4.5–6.6	4.2–6.6	3.7–3.9
Stack efficiency (% LHV) [59,62,64]	63–71	60–68	100
System efficiency (% LHV) [59]	51–60	46–60	76–81
Lifetime of stack (kh) [59,66]	60–120	60–100	8–20
Degradation (%/a) [59]	0.25–1.5	0.5–2.5	3–50
Capital cost (USD/kW) [59,66]	880–1650	1540–2550	>2000
Maintenance cost (% of investment/year) [59]	2–3	3–5	n.a.
Advantages [67]	Low capital cost; stable operation	High H_2 purity, fast start-up; compact system	High efficiency; low capital cost
Disadvantages [67]	Corrosive system; low H_2 purity; slow start-up	High cost of membranes and electrodes; high pressure; acidic	Instability causing safety issues
Technology maturity [67,68]	Commercial	Near commercial	Demonstration

Fig. 5.1 Characteristics of Alkaline, Proton Exchange Membrane, and Solid Oxide electrolysis

Basically, Community Choice Aggregation means a village, town and city have the opportunity to lower their energy cost, carbon emission from a shared purchasing model. It allow us to purchase the electricity that generate by renewal sources from other areas. If we can maintain a stable electricity input, SOEC is also a completive option because it as a high efficiency and the waste heat can be used in heating.

5.2 The cost of elctrolyzers:

Electrolysis is currently an expensive way to generate hydrogen. The high costs of green hydrogen come from the high capital costs of renewable energy and electrolyzers and are exacerbated by the inefficiencies of current electrolysis methods.

It is important to note that these electrolysis technologies are undergoing a large period of development and study. However, the research and development being done on electrolysis is predicted to increase electrical efficiency and reduce the cost of the systems over time. Figure 5.2 below shows the long-term forecasts for AEL and PEM technologies to top out around 70% efficiency with costs roughly half of what exist today. SOEL technology holds promise for 90% efficiency and costs roughly one-fifth of what exists today (IEA, 2019). This is indicative of the younger nature of SOEL.

	Alkaline electrolyser			PEM electrolyser			SOEC electrolyser		
	Today	2030	Long term	Today	2030	Long-term	Today	2030	Long term
Electrical efficiency (%, LHV)	63–70	65–71	70–80	56–60	63–68	67–74	74–81	77–84	77–90
CAPEX (USD/kW_e)	500 – 1400	400 – 850	200 – 700	1 100 – 1 800	650 – 1 500	200 – 900	2 800 – 5 600	800 – 2 800	500 – 1 000

Notes: LHV = lower heating value; m^2/kW_e = square metre per kilowatt electrical. No projections made for future operating pressure and temperature or load range characteristics. For SOEC, electrical efficiency does not include the energy for steam generation. CAPEX represents system costs, including power electronics, gas conditioning and balance of plant; CAPEX ranges reflect different system sizes and uncertainties in future estimates.

Fig.5.2 Future efficiencies and costs of electrolysis (IEA, 2019)

6. Compression storage and dispensing

6.1. Compressor

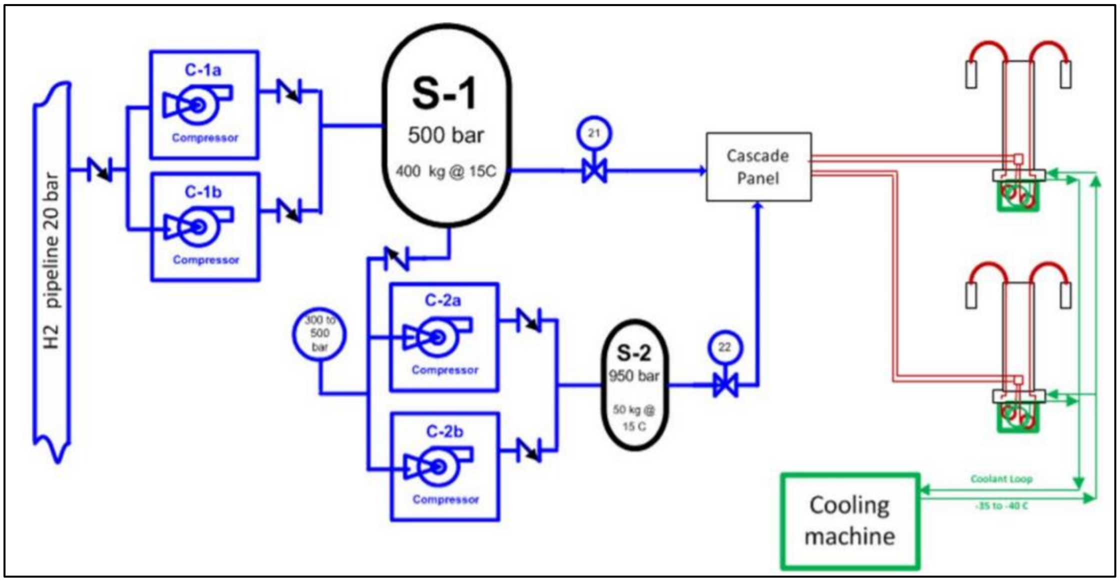


Figure 6.1. Hybrid cascade model

The approach in this project to compress hydrogen was to use one set of compressors to fill a 400- to 500- (450-) bar storage tank and a second set of compressors to draw hydrogen from the 450-bar storage tank to fill the cascade system (NREL, 2014).

According to the report by NREL, the two-stage diaphragm compressor PDC-13 could satisfy the hybrid cascade model and raise the pressure to 950 bar through two stages. The hydrogen will be pressed to 500bar in stage one and then pressed to 950bar in stage 2. The two stages operate independently, allowing each compressor stage to operate over a wide range of mass flow (and suction pressure). The configuration of PDC-13 compressor is shown in figure 6.1. The relationship between mass flow and suction pressure for this two-stage compressor is shown in Table 6.1.

Figure 6.2. Two stage PDC-13 compressor

First Stage Capacity: Discharge 500 bar					
Suction Pressure (PSIG)	5,816	4,350	2,900	1,450	725
Suction Pressure (bar)	401	300	200	100	50
Mass Flow (NM^3/hr)	1,420	1,079	750	400	200
kg/h	128	97	67	36	18
kg/d (max)	3,062	2,327	1,618	863	431

Second Stage Capacity: Discharge 950 bar				
Suction Pressure (PSIG)	7,500	7,250	5,800	4,350
Suction Pressure (bar)	517	500	400	300
Mass Flow (NM^3/hr)	811	790	700	500
kg/h	73	71	63	45
kg/d (max)	1,750	1,704	1,510	1,079

Table 6.1 specification of the two-stage compressor

There is no information about the cost of such compressor. However, the compressor costs estimated by the H2A model in distributed production scenario could be taken as reference. The information provided by H2A model is listed in table 6.2. The estimated compressor cost in our case is taken as $297,185 since only 1 PDC-13 compressor can meet the compression flow demand.

	H2A Distributed Production Scenario	
	Current	Future
Compressors On-site	3	1
Isotropic Efficiency	65%	80%
Designed Flow Rate (Each)	63 kg/h	126 kg/h
Actual Shaft Power (Each)	177 kW	287 kW
Motor Rating (Each)	208 kW	335 kW
kWh/kg	3.30	2.66
Compressor Costs (Each)	$297,185	$259,082

Table 6.2 Modeled compressor cost in distributed production (Godula-Jopek, 2012).

6.2. Hydrogen storage

Types of pressure vessels for hydrogen storage. (NREL, 2014).

I Steel; maximum pressure: 20 MPa Aluminum; maximum pressure: 17.5 Mpa Gravimetric hydrogen density: 1 wt%

II Metal tank (aluminums/steel) with fiber composite (glass, aramid, and carbon) around the metallic cylinder; maximum pressure: 30 Mpa

III Composite material (glass, aramid, and carbon fibers) tank with a metal liner (aluminum, steel) maximum pressure: 44 Mpa

IV Composite material (carbon fiber) with a polymer liner (high density polyethylene (HDPE) maximum pressure: 70 Mpa and even more Gravimetric hydrogen density: 11.3 wt%

The storage vessels used for the high-pressure cascades, however, have different descriptions for the 350-bar and the 700-bar stations, as one would expect. In the Nexant report, based on HDSAM Version 2, which describes only a 350-bar filling station, the high-pressure cascade vessels are described as being ASTM SA372, Grade J, Class 70 vessels. CP Industries provided a quote at the time of report preparation for cylinders with dimensions: OD 16 in (0.4 m), length 30 ft (9.1 m), wall thickness 1.65 in (0.04 m). Using the quoted freight on board (FOB) price of $18,000 per vessel yields an uninstalled cost of $843/kg of hydrogen stored at 430 bar (6,250 psig).

The Type 4 cylinder is already being used in Japan and North America, with a working pressure of 950 bar and a MAWP of 1,050 bar. These have a 9-ft3 (255-L) internal volume and are already being used for ground storage. The cylinders are 79 in (201 cm) long with an OD of 24 in (60 cm). Each Type 4 vessel holds 11.6 kg of hydrogen at 875 bar. A bank of three vessels connected as a cascade would hold 34.8 kg. To achieve the 196 kg required by the H2A for the 1,000- kg/d distributed generation scenario would require six banks of three cylinders and would hold 209 kg of hydrogen. The total cost would be about $215,000 as shown in table 6.3.

Vessel type	H2 Vessel at 875 bar	Number of Vessels needed	Total H2 in Storage	Capital cost	$/kg
Vendor D Type 4	34.8kg	6	209kg	$215,000	$1029

Table 6.3. storage vessel specification

6.3. Dispenser

The current cost estimates range from $100,000 to $180,000 for a two-hose dispenser, whereas DOE's current CSD cost modeling assumes that a two-hose dispenser costs $54,000 at high market penetration. A dual-hose CNG dispenser with flow meters, credit card reader, etc., currently costs more than $45,000, and CNG dispenser costs are not expected to decrease much in the near term. The cost estimation by NREL is listed in table 4. In our distributed case, the cost of dispensers is about $161,000, and the cost of cooling system is about $246,000.

	H2A/HDSAM Default Values	Panel Base Case	Optimistic	Pessimistic
Pipeline				
Dispensers (2)	$107,000	$189,000	$165,000	$236,000
Cooling System	$197,000	$227,000	$187,000	$283,000
Distributed				
Dispensers (3)[a]	$161,000	$283,000	$248,000	$355,000
Cooling System	$246,000	$227,000	$187,000	$405,000

Table 6.4. cost estimation of dispenser

The total CSD equipment capital cost for a refueling station with capacity if 1000kg/L is about $919,185. The installation factor is assumed as 1.3 and the additional cost is assumed as 23%, so the total CSD capital cost is about 160% of the equipment cost which is $1,470,000.

8. Cost of hydrogen production

8.1. Comparison with traditional prices

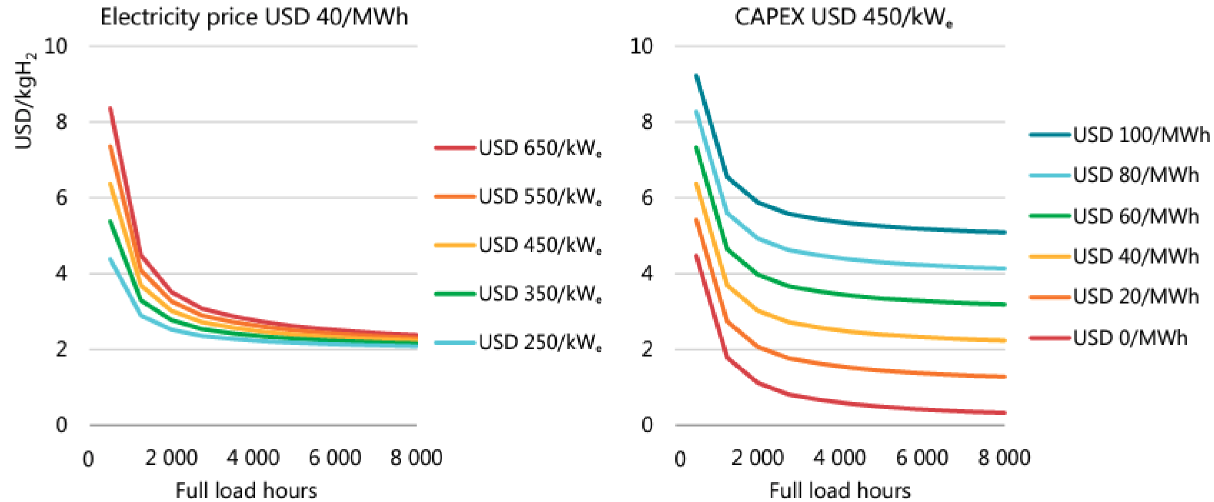
Hydrogen production comes from a variety of methods. As previously discussed, there are three primary types of hydrogen production that have gained attention in the scientific community. Grey hydrogen, which is produced from steam methane reforming, accounts for much of the hydrogen produced today. Grey hydrogen costs, on average, $1.30/kg (NREL, 2009). Using carbon capturing technologies with steam methane reforming costs just slightly higher at $1.55/kg (NREL, 2009). Other sources put the cost of grey hydrogen around 1.50 Euros/kg. (van Renssen, 2020)

Green hydrogen currently costs about $4.50/kg to produce (NREL, 2009). The U.S. DOE puts a rough estimation of current green hydrogen production at $5/kg (Bade, 2022). Van Renssen estimates cost of green hydrogen to be in the range of 3.50-6.00 Euros/kg. While there is not clear agreement on the exact prices of hydrogen from different sources, there is clear agreement on 1. grey hydrogen is significantly cheaper currently and 2. the cost of green hydrogen will decrease dramatically within a decade. Prices of green hydrogen are expected to become competitive with grey hydrogen long-term.

Beyond noting the existing prices, it is important to pay attention to the major factors influencing cost, namely price of electricity and capital cost of electrolyzers. There is a balance between having enough capacity while reducing capital costs. Underutilization of electrolyzers can make costs of hydrogen much greater in cases of low utilization. The degree to which a production facility is utilized or operates at full capacity, otherwise known as the capacity factor, has a large influence on the total cost of hydrogen. The cost of hydrogen production is dependent not only on capital costs but also on electricity price.

Both factors also play a role with the utilization of production equipment to determine the cost of hydrogen. Fig 8.1.a shows how these cost variables interact with each other. Important to note in this chart is that a capacity factor under 25%, roughly 2200 hours of operation a year poses significant effects on prices whereas above 25% capacity has little impact on the overall price of hydrogen (IEA, 2019). Also, regardless of the utilization of the electrolyzer, electricity price plays a large role in determining the cost of hydrogen. Both assumptions of LCOE for electricity and capital cost of electrolyzers in figure 8.1.a are presented for future scenarios and are favorable for current hydrogen production.

Fig. 8.1.a. Cost of hydrogen/kg as a function of electricity and capital costs (IEA, 2019).



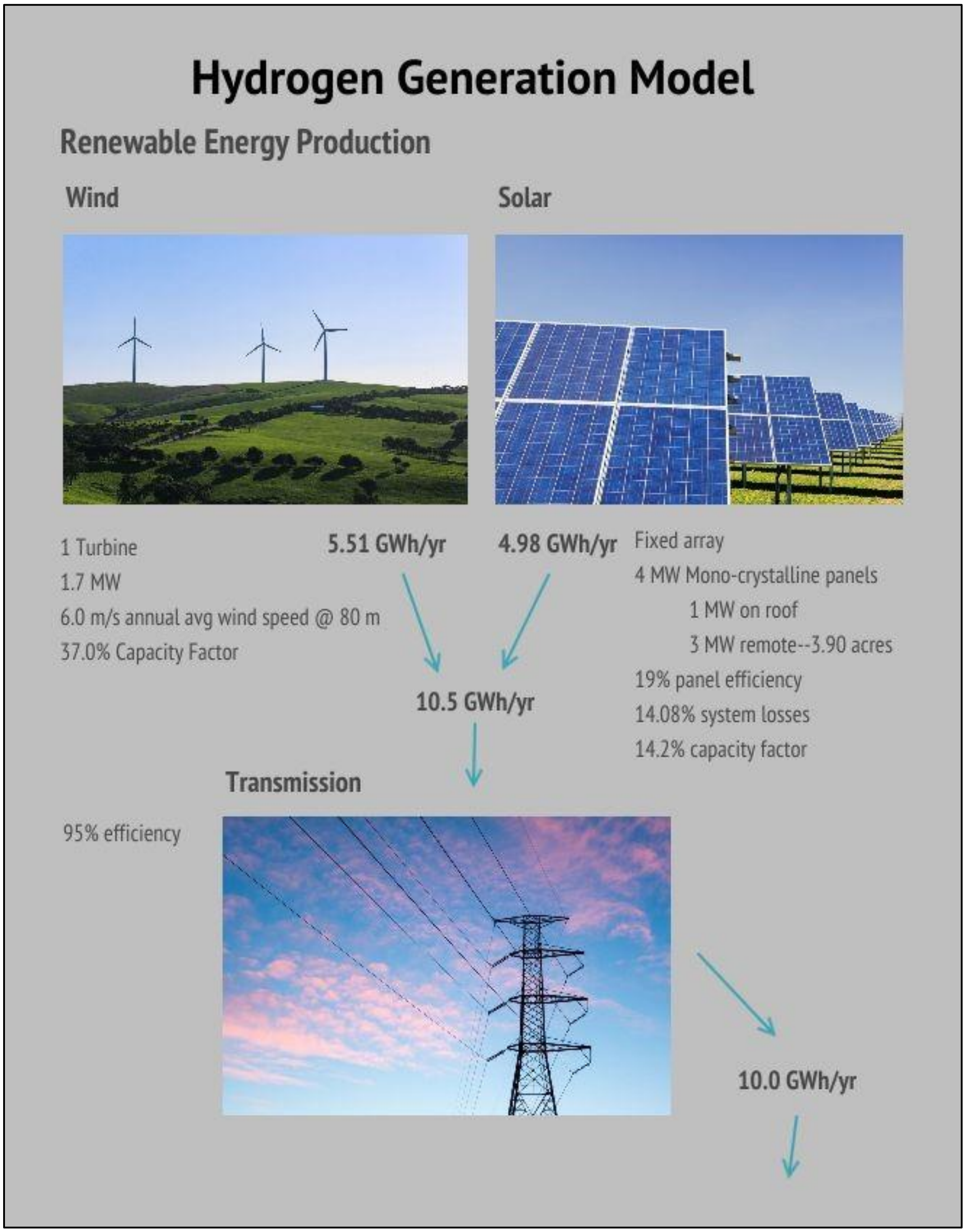
Notes: MWh = megawatt hour. Based on an electrolyser efficiency of 69% (LHV) and a discount rate of 8%.

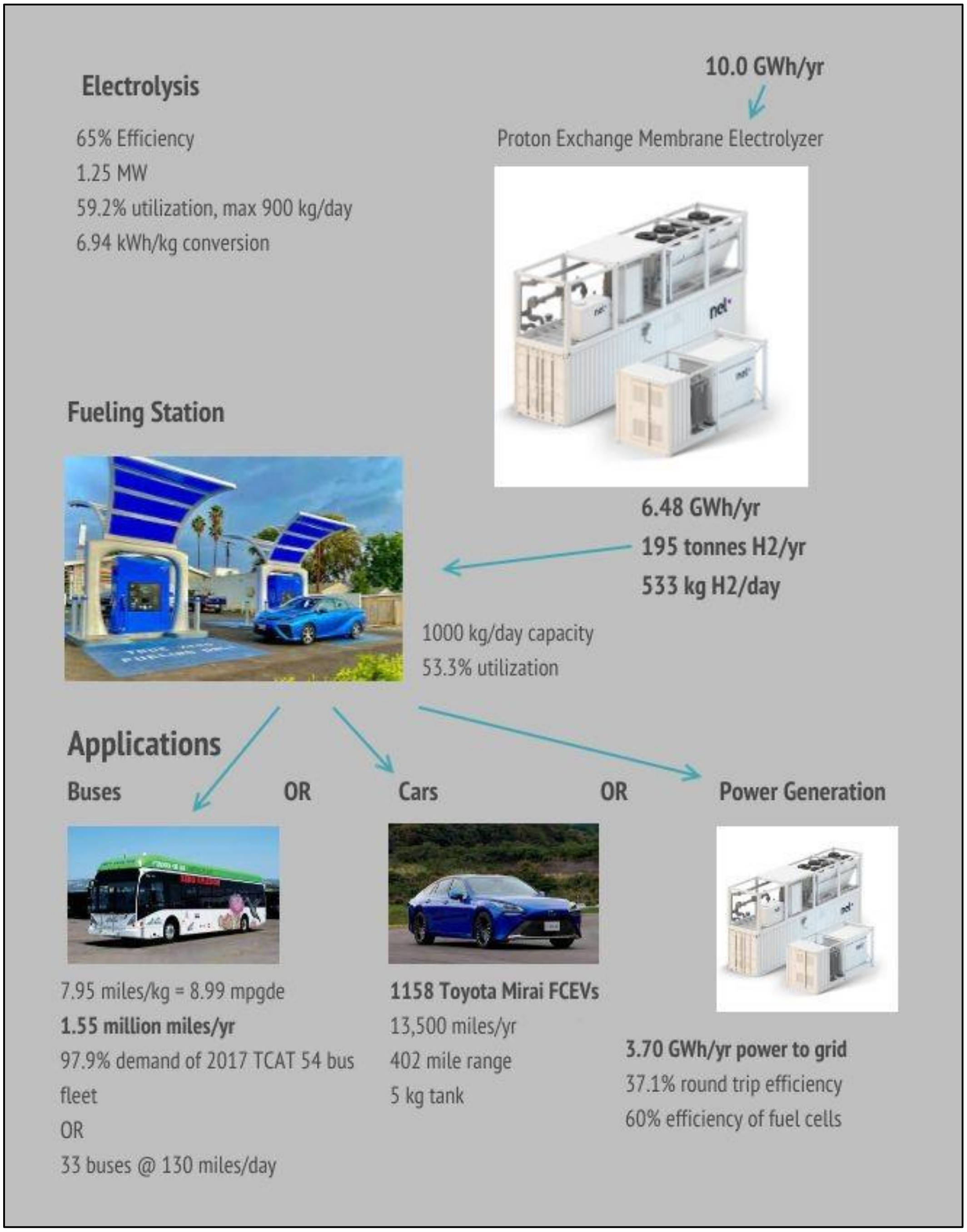
Source: IEA 2019.

The graph on the left charts the cost of hydrogen in scenarios where electricity price is fixed at \$40/MWh and capital cost is varied. The graph on the right fixes the capital cost at \$450/kW of electrolyzer and varies the price of input electricity.

8.3. Model Integration--Peter

Figure 8.3.a Hydrogen Generation Model





The model presented above aims to highlight the components of the production process for green hydrogen and estimate output that would be achievable with modern technology capabilities. The assumptions and model in full can be viewed in Appendix B. Detailed explanations of the reasons for the choices of assumptions for each of the components can be found in greater detail in each of the corresponding sections.

The production of the wind farm is estimated using a single 1.7 MW wind turbine. The assumed a 6.0 m/s annual average wind speed at 80 m, and was adjusted to a 100 m hub height with a corresponding wind speed of 6.27 m/s. Combined with the assumption of the power curve shown in Appendix A, the single 1.7 MW turbine wind farm produces 5.51 GWh/yr. The expected capacity factor from this modeled wind farm is 37.0%.

The production of the solar arrays includes the output of the 1 MW array on the roof plus the 3 MW array on the ground. This array will be fixed at an angle of 35.33 degrees to maximize capturing of year-round insolation. System losses from the arrays are assumed to be 14.08%. The array consists of 19% efficiency monocrystalline panels. The efficiency of the panels installed could vary based on the amount of capital available to invest in high efficiency panels. The estimated output of these two arrays combined is 4.98 GWh/yr with a capacity factor of 14.2%. Both the production of wind and solar represent favorable productions as there is no consideration for downtime for maintenance, repair, or curtailment from dispatch.

Combined, the production from the wind and solar sources total 10.5 GWh/yr. The energy from the wind and solar farms must be delivered to the location of the electrolyzer, which will be conveniently located at the ChainWorks plant with a fueling station. The transmission losses are assumed to be at the national average of 5%, resulting in 10.0 GWh/yr of green electricity being delivered to the electrolyzer (Chen, 2018). The transmission from the 1 MW solar array on the roof would have significantly reduced losses compared to the distributed 3 MW solar array and wind farm. Actual transmission losses could be reduced by locating production closer to the ChainWorks plant. Locating sites for the solar array and wind farm will have to consider the favorability of the site for wind or solar production and weigh the effect of greater transmission losses for sites further away from the ChainWorks plant.

The electrolyzer chosen for this project is a proton exchange membrane electrolyzer. Proton exchange membrane electrolyzers can better accommodate intermittent loading than their solid oxide counterparts. Additionally, they have a reasonable peak operating temperature of 100 degrees Celsius. While this operating temperature is reasonable, it still is hot enough for potential to be coupled with a combined heat and power system to provide heating at the ChainWorks facility. Proton exchange membrane electrolysis has sufficient efficiency currently that is expected to rise and as the adoption of PEM technology is developed for usage in the transportation industry.

While PEM electrolysis is more expensive than its alkaline counterpart, these prices are expected to equalize in the long-term. Electrolysis processes are expected to be 65% efficient. The size chosen for the electrolyzer is 1.25 MW, following similar commercially available container-sized electrolyzers (Nel ASA, 2021). Running at 100% of nameplate capacity, the electrolyzer can produce 900 kg of hydrogen per day. The output of the electrolyzer given an annual input of 10.0 GWh yields 6.48 GWh per year. This is equivalent to 195 tonnes of hydrogen per year or 533 kg per day. The conversion between GWh of electricity and kg of hydrogen assumes an energy content of 120 MJ/kg of hydrogen (Malloy, 2019). The 1.25 MW electrolyzer has an annual average utilization of 59.2%.

The electrolyzer will provide a supply of hydrogen to a fueling station. The fueling station is assumed to have a capacity to dispense 1000 kg per day and service both buses and FCEVs. The 533 kg of hydrogen produced per day is expected to vary based on electricity price and renewable generation. Sufficient capacity to store produced hydrogen is critical to the success of the project. The service of mitigating intermittency as well as providing capacity on the grid relies on a significant amount of storage. In this model, we assume no losses in storage or energy consumption needed for storage. As production needs to be scaled and space requirements for storage increase, the need for liquefication will grow. This process requires roughly 30% of the energy content in the hydrogen itself (Energy.gov, 2021). Consumption from busing services is expected to remain relatively constant year-round and thus present less need for storage.

Considerations for storage are discussed in more detail in the storage section. Currently, this project relies on a fleet of 4 small storage tanks, totaling 105 kg of capacity. This small storage capacity will inhibit the ability of the project to provide the grid with ancillary services and earn revenue associated with those services. This size of storage will also reduce the capital costs of the facility and energy expenses from compressors and liquefication. More importantly, it reduces the significant losses that occur from hydrogen stored under high pressure.

The hydrogen produced can be used to provide energy for several different applications. Fuel cell electric buses and vehicles can be refueled from a refueling station. Additional hydrogen can be used to provide capacity services to the grid, acting as a battery. An electrolysis production of 195 tonnes per year can yield 1.55 million miles of bus travel at a fuel economy of 7.95 miles per kg, equivalent to 8.99 miles per gallon of diesel (NREL, 2021).

This fuel economy is what current fuel cell buses part of AC Transit in the Bay Area achieve. This would provide TCAT with 97.9% of its 2017 fuel needs if its fleet were entirely FCEBs (TCAT, 2018). The 2017 fleet consisted of 54 buses, equating to 10.0 kg of hydrogen per bus per day on average. This is also equivalent to 79.8 miles per bus per day. This consumption is quite low and is a third of what the California Fuel Cell Partnership (2013) cite for typical consumption per bus at 30 kg per day. Assuming an arbitrary higher range driven per day of 130 miles supports 32 buses.

The full output of 533 kg per day could alternatively be used to provide personal FCEVs with fuel. Using the full output from the electrolyzer could support 1158 Toyota Mirai FCEVs, assuming 13,500 miles driven annually, the national average. The Toyota Mirai achieves a range of 402 miles on 5 kg of hydrogen.

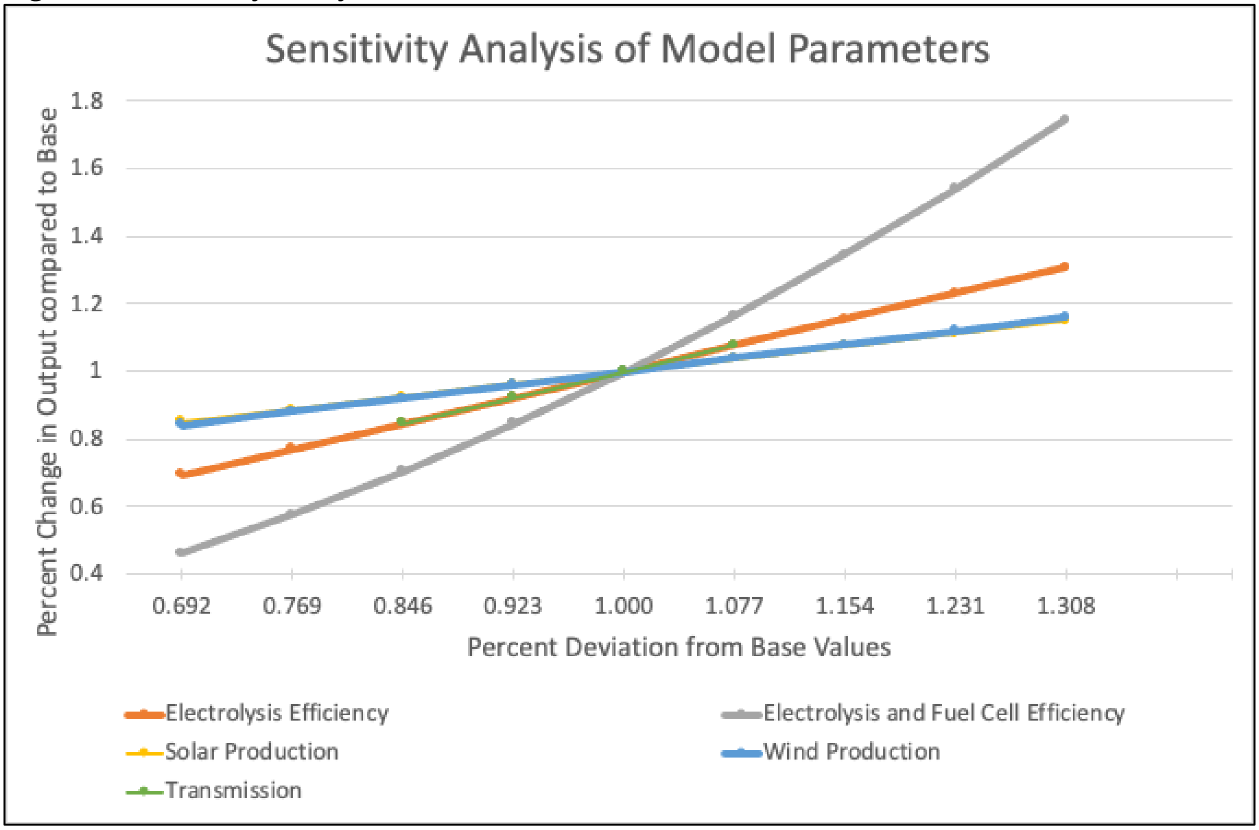
The hydrogen produced from the electrolyzer could also be stored and used on the grid to produce electricity during periods of peak production and ramping up. Hydrogen could be accumulated on a diurnal basis generating reserves for periods of additional capacity need both for daily fluctuations and peak summer and winter loads. Assuming 95% transmission efficiency to end users puts 3.70 GWh through the grid to consumers if the hydrogen was solely used to produce electricity. This assumes that there would be a route via fuel cells to generate electricity from hydrogen and the corresponding efficiency would be 60%. This results in an overall round trip efficiency of 37.1% from renewable generation output to consumption.

Overall, this model aims to illustrate key processes in green hydrogen production and use and estimate quantities of production achievable given current technological capabilities. One of the biggest simplifications of the model involves a lack of consideration for the space and energy requirements for hydrogen storage. The model is strongly tied to the Ithaca area and the available electricity generation options.

8.4. Sensitivity analysis

A sensitivity analysis was conducted on the model to gain insight into the characteristics of the hydrogen generation system itself. Parameters in the model were changed a percentage of their base values. Then the changes in output of the electrolyzer in kg of hydrogen per day was observed. Figure 8.4.a shows a graphical of the analysis's output. A tabular from can be found in Appendix C. Base values of the model are shown below in figure 8.4.b.

Fig 8.4.a. Sensitivity Analysis of Model Parameters



The first result from the sensitivity analysis is the inherent stability in electricity production. Changes in either wind production or solar production resulted in smaller effects to the hydrogen output than perturbations to the individual outputs of the generation sources themselves. Because the generation of electricity is shared between two sources and there is no assumed correlation between wind and solar production, fluctuations in power generation in either source were lessened by the production of the other source. Beyond the seasonal compliments of wind and solar resources, this is another way this dual-source generation works synergistically. The input power for electrolysis is expected to be stable.

This stability is also strengthened by the characteristics of wind energy. Vanek et. al. (2012) show that in a given year, wind production most always hovers within 10% of its base value, rarely deviating further than 10% of its average production. To summarize, the wind and solar production were changed a percentage from their respective base values and the resulting changes in kg per day of hydrogen were roughly half the percent change in individual generator production. This is reflective of the dual generation characteristic of the power supply. Changes in either value of generation did not change the efficiency of the system.

Figure 8.4.b Base values of model and sensitivity analysis

Base Values				
Electrolysis Efficiency	Electrolysis and Fuel Cell Efficiency	Solar Production	Wind Production	Transmission Efficiency
65%	65% and 60%	4.98 GWh/yr	5.51 GWh/yr	95%

The second result from the analysis showed the direct linear correlation between the output in kg per day and both transmission efficiency and electrolyzer efficiency. Changes in electrolyzer efficiency resulted in a 1:1 ratio of change in the output. Raising the efficiency of the electrolyzer assumption, raised the output by the same percentage the electrolyzer efficiency was raised. The same appeared for transmission and any singular efficiency assumption of the model. The transmission base value was assumed to be 95%, the national average of transmission efficiency. Because the processes electrolysis and transmission change efficiencies of the system components, not only do changes in these efficiencies change the output of the model in kg per day but they also affect the round trip efficiency of the system. To clarify, this round trip efficiency is only being considered for the application of putting energy back on the grid. Wind and solar output affect production by varying total power provided for electrolysis while changes in transmission and electrolysis affect the output by changing the efficiency of the processes involved in producing hydrogen.

Since the electrolyzer efficiency has a greater effect on the output of the system, the analysis was designed around the assumption of 65% electrolyzer efficiency. The intervals given on the horizontal axis each correspond to a 5% change in electrolyzer efficiency, meaning, the 0.923 percent change represents 60% efficiency and the 1.077 percent change represents 70% electrolyzer efficiency.

Lastly, a scenario was considered where hydrogen is being used to provide capacity to the grid. This process is reliant on both the performance of the electrolyzer and the performance of the technology used to generate electricity from hydrogen--in this case using both an electrolyzer to produce hydrogen and then fuel cells to produce electricity. This scenario varied the efficiencies of both processes. The result was compounding and shows a quadratic relationship between the adjusted input variation and the modeled output. In this case, the output is not the kg of hydrogen produced per day but the round-trip efficiency of energy produced by the solar and wind generation resources. This relationship highlights the importance of electrolysis in generation and the large effect that proton exchange membrane technology efficiency has on the performance of the system for providing capacity services.

The sensitivity analysis conducted here yields several insights for this project. Namely, the analysis shows that the model developed is sensitive to the efficiency of the electrolyzer, particularly when being used for capacity support for the grid. Secondly, the analysis shows the benefit of having diverse sources of power generation. Diversification of generation resources leads to a more stable supply of power. Stability of generation is an important consideration given one of the potential users of hydrogen is a busing system, which will require a near constant level of fueling.

9. Applications:

9.1. Hydrogen bus and relevant infrastructure

Subsequent designs have been developed by industry and there are now more than 80 full-size fuel cell electric buses (FCEB's) currently in operation in various locations all over the world. The key components of the hydrogen fuel cell bus are shown below.

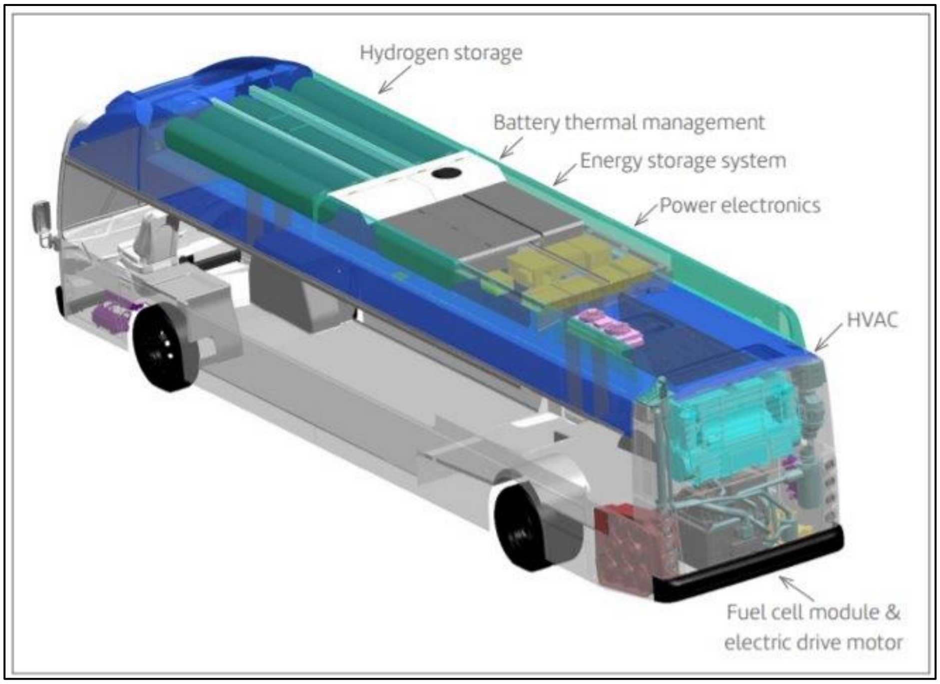


Figure 9.1 key components of hydrogen fuel cell bus

With up to 300 miles between fill-ups, fuel cell buses offer a comparable range to diesel-powered buses. Fuel cell electric buses operate a full 18-hour shift on the road with a single 10-minute refilling at night.

California's Alameda-Contra Costa Transit Agency (AC Transit) is the largest public bus-only transit agency in California. They have 27 active zero emission bus including 21 fuel cell bus till 2020. By early 2023, they are expecting to have 70 zero emission bus's in service. (CaFCP, 2019).

They have fuel cell buses that have been in operation for over 30,000 hours. This is equivalent to operating a bus on a 14-hour daily schedule, 5-days per week for 6.9 years with no replacement to the fuel cell stack and the core engine component which shows the durability of hydrogen fuel cell buses.

Hydrogen filling station for buses

Two hydrogen stations for bus refueling built by AC transit will be introduced to inspire our project.

The hydrogen station at the Oakland Division was built in 2014 at a total cost of $6,300,308. The station includes a 9,000-gallon of liquid hydrogen storage tank, ambient vaporizers, an IC-50 ionic compressor, and 360 kg of high-pressure gaseous storage. The station also includes an electrolyzer that produces up to 65 kg of green hydrogen per day using the district's solar assets as an energy source. Two dispensers were installed in the fuel island that are aligned with the diesel dispensers making the bus servicing process seamless. This station has a fueling capacity for 13 buses per 12-hour fueling window (Fuel Cells Bulletin, 2021).

The Oakland hydrogen station is maintained by a O&M contract with a vendor. The monthly cost of this O&M contract covering operations, preventative maintenance, corrective maintenance, and LH^2 tank maintenance is $15,577 which includes a $2,213 monthly allowance for corrective maintenance. Operations includes maintaining a remote monitoring and alarm system to support 24/7 operations by dispatching a technician upon alarm. Preventative maintenance includes regular and planned activities to any of the equipment on a weekly, monthly, or annual basis. Monthly inspections and certifications of liquid storage (hydrogen or nitrogen) are also included. The District plans to upgrade the Oakland hydrogen station with liquid pumps once funding is secured.

Figure 9.2. Oakland hydrogen station

The hydrogen station at the Emeryville Division was originally built in 2011 at a cost of $5,100,000 for only the heavy-duty bus fueling portion of the project. In 2020, the station was upgraded at a cost of $4,424,644. Upgrades to the station includes a 15,000-gallon liquid hydrogen storage tank, dual ADC MP-100 Cryogenic Pumps, high pressure vaporizers, and 360 kg of high-pressure gaseous storage. Two dispensers were installed in the fuel island that are aligned with the diesel dispensers making the bus servicing process seamless. The upgraded station can fuel 65 FCEBs in the 12-hour fueling window (Fuel Cells Bulletin, 2021).

The Emeryville hydrogen station is maintained by a O&M contract with a vendor. The monthly cost of this O&M contract covering operations, preventative maintenance, corrective maintenance, and LH^2 and N^2 tank maintenance is $11,850 which includes a $750 monthly allowance for corrective maintenance. Operations includes maintaining a remote monitoring and alarm system to support 24/7 operations by dispatching a technician upon alarm. Preventative maintenance includes regular and planned activities to any of the equipment on a weekly, monthly, or annual basis. Monthly inspections and certifications of liquid storage (hydrogen or nitrogen) are also included.

9.2. Car-park Power Plant

Fuel cell vehicles can provide more efficient and cleaner transportation. However, we use our cars for transportation only 5% of the time. When parked, the fuel cell in the car is wasted. Reasonably, we can use our fuel cell car as a power plant when it is not used for driving, namely, when it is parked somewhere. At this parking place we need at least to be able to connect the car to the electricity grid. And if we want to use also the heat and the fresh water that is produced as a waste product, we need to extract the heat and water from the fuel cell and bring this to a heat network and a water grid. A logical place to do this is a parking garage.

Car-Park Power Plant (Wijk and Verhoef, 2014) integrates a hydrogen production subsystem through natural gas reforming to enable the production of electricity, heat, and water by the FCVs as well as hydrogen to be used in an external pump station. At the parking place the fuel cell in the car will be automatically connected to the electricity grid, a hydrogen grid, a water grid and a control system. Hydrogen is produced at the gate of the car park from gas by steam reforming or from electricity by electrolysis and will be supplied to the fuel cell. The hydrogen under atmospheric pressure will be directly fed to the fuel cell. The fuel cell converts the hydrogen directly into electricity and hot demineralized water.

The produced electricity, heat and fresh water can be fed into the respective grids. Therefore, in order to improve the utilization of renewable energy generation, we can introduce hydrogen into the grids and use excess renewable energy to electrolyze water to produce and store hydrogen in hydrogen storage tanks. Fuel cell vehicles can convert hydrogen into electricity to supply the grid's energy demand when the grid is short of energy, and fuel cell vehicles can be used for transportation.

Hydrogen can be purchased from a hydrogen-producing company and used for the transportation of fuel cell vehicles. Fuel cell vehicles are particularly suited to provide spinning reserves and peak power to the grid. In contrast to plug-in electric vehicles, fuel cell vehicles can be operated continuously and have very low emissions (Lipman, et.al., 2004). Hydrogen, as a clean energy with high calorific value, is attracting wide attention. Therefore, the car as a power plant (CaPP) is presented to introduce a controllable energy system. Considering that the average driving time of vehicles is less than 10% of the whole day, vehicles can generate electricity by combusting hydrogen in a cleaner way than other power systems when they are parked, and there is a huge potential for fuel cell vehicles to take replace traditional power plants or reduce the number of new plants in the future. Therefore, the synergies between hydrogen and electricity can be explored to increase the benefits of microgrids.

An averaged sized car park with 500 cars with a fuel cell capacity each of 100 kW is a power plant of 50 MW (Fernandes, et.al., 2016). When operating such a power plant with a load factor of 4,000 hours such a car-park power plant generates 200,000,000 kWh, which is 200 GWh. In 2020, the average annual electricity consumption for a U.S. residential utility customer was 10,715 kWh. A car park with 500 cars is able to generate all the electricity for 18,665 houses.

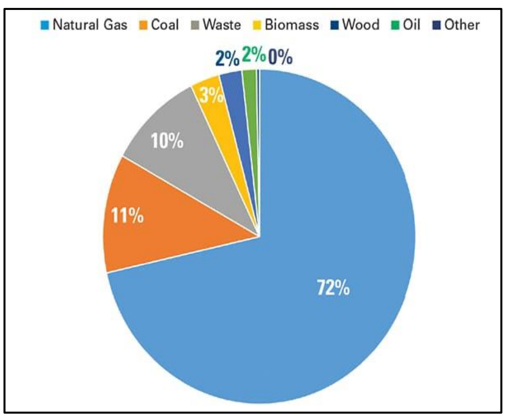
10. Discussion, Conclusion, and future work:

There are many challenges present in incorporating hydrogen technology. Many of these challenges arise from the infancy stage of development of hydrogen technology. In choosing to locate electolyzers on site to reduce the transportation needs and costs, the production available to the site is then dependent on the electrolyzer at the site. This constrains the site's production to the capacity of the electrolyzer even though there is a significant amount of flexibility to adjust production around the rated capacity of the electrolyzer. In situations where small amounts of hydrogen are needed, this could create issues of capital investments having low utilization and low economic returns because of underutilization of electrolyzers and lack of economies of scale.

Additionally, more opportunities will arise from technological development in the future. Proton-exchange membrane electrolyzer technology is less developed than its alkaline counterpart. However, proton-exchange membrane electrolysis holds promise both for increased overall efficiency if the waste heat from the 100 degrees Celsius operating temperatures is used for combined heat and power. Coupling an electrolyzer to a combined heat and power system can provide a 25% boost to overall efficiency (U.S. DOE, 2016). The challenge of any electrolyzer technology will be weighing capital costs against the high payoff from higher efficiency. Electrolysis technologies are developing at a rapid pace. As electrolysis technologies develop, their costs, efficiencies, and outlooks will change. It will be critical to examine the benefits and costs of changes and performances in the future.

10.1 CHP

CHP (Combined Heat & Power) system consists of electric generation, most typically from natural gas (Figure 1), but also from diesel, coal, biomass, solar, geothermal, or nuclear, with a system that captures the heat that's produced and typically lost. The excess heat, often steam, can be used for heating—and ever more frequently cooling—and domestic hot water. Many new CHP systems can provide backup power during grid outages. The chart below shows a breakdown of the fuels used to power U.S. CHP installations at the end of 2017 as a percentage of total capacity. Natural gas supplied the vast majority of systems.



Nearly two-thirds of the energy used by conventional electricity generation is wasted in the form of heat discharged to the atmosphere. Additional energy is wasted during the distribution of electricity to end users. By capturing and using heat that would otherwise be wasted, and by avoiding distribution losses, CHP can achieve efficiencies of over 80 percent, compared to 50 percent for typical technologies (i.e., conventional electricity generation and an on-site boiler).

A 2016 DOE study, "Combined Heat and Power (CHP) Technical Potential in the United States" says, "Across all CHP categories, there is estimated to be more than 240 GW of technical potential at over 291,000 sites within the U.S." Furthermore, it says, "In contrast to the existing facilities with installed CHP, which are heavily concentrated at large industrial and manufacturing facilities, a significant portion of the remaining technical potential for on-site CHP in the U.S. is located in commercial facilities."

The DOE has a long-stated goal of having 20% of generating capacity in the U.S. from CHP. In the U.S., the growth of microgrids is meshing nicely with CHP. Microgrids solve reliability and cost issues. Combining the power with heat and cooling offers additional efficiency, environmental, and cost benefits.

Outside the U.S., a 2015 POWER analysis of CHP around the world ("Global CHP Still Struggling to Break Out of Its Niche") found mixed prospects. The article says, "Despite its efficiency and environmental benefits, combined heat and power generation has languished at around 10% of worldwide capacity for more than a decade." International Energy Agency (IEA) statistics showed that in 1990, global electricity production from CHP amounted to about 14% of the total. By 2000, CHP had dipped to 10%, where it has remained mostly stable since. In the European Union, for example, CHP in 2017 accounted for 11% of electric generation.

European countries are aggressively pushing CHP. Germany has a goal of doubling its electricity from CHP to 25% by 2020. The UK offers financial incentives, including grants, and a favorable regulatory environment. The IEA's CHP collaborative says the expansion of CHP in France, Germany, Italy, and the UK would result in energy savings of 465 TWh by 2030, and up to a 29% increase in each country's total generation from CHP.

India is also ripe for CHP. Supplying heat is not a major issue in much of India, but cooling is another matter. In Bangalore, India's Silicon Valley, a joint venture of Singapore's Information Technology Park, Tata Industries, and the Karnataka state government developed an integrated, self-contained CHP complex serving multi-storied offices, residential, and recreational facilities supporting more than 130 companies with 20,000 employees. According to a 2008 IEA case study, the array of gas-fired turbines serves a peak power demand of 54 MW. Each unit recovers heat for chilled water. Total energy efficiency of the system, according to the IEA, is 67%.

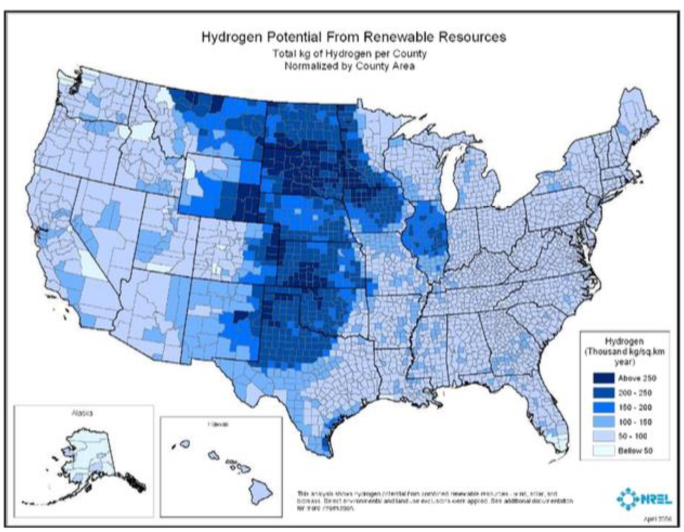
10.2 Future prospects

While the current chosen electrolyzer for this application is proton-exchange membrane technology, there is potential for other electrolyzer technologies to be employed in the future. Solid oxide electrolysis can operate in reverse, generating electricity from hydrogen inputs. This removes the need for additional technology of fuel cells to provide capacity for the grid in times of shortage. Solid oxide electrolysis currently is just becoming commercially available and poses high capital costs as well as much potential for increased efficiency in coming years. Additionally, the 800 degrees Celsius operating temperature will be something that has to be accommodated. The ancillary services provided by a reversible electrolysis present possibility for additional revenue streams to support the incorporation of electroyzers connected to the grid. This is dependent on the availability of sufficient storage to allow the electrolyzer to utilize this ability.

One area of investigation that remains particularly interesting economically that arose from this project work is the installation of electrolyzers around areas with high variable production with low demand. Areas that have large amounts of renewable energy installed that also lack transmission to users frequently experience negative locational marginal pricing. Due to the high production without the ability to use electricity means that prices of electricity are sometimes negative and frequently hover around 0, or the marginal cost of renewable production. This low and negative pricing is exacerbated by renewable energy credits and subsidies that encourage more renewable projects to be built and that create economically viable pathways for generators to make profits even when selling at negative prices.

Figure 10.3.a below shows the potential hydrogen production available from renewable sources by county (Levene, et. al., 2005). This figure suggests higher potential for green hydrogen production in the Midwest. Electrolyzers located in these areas could take advantage of lower cost electricity, a major factor in the end cost of green hydrogen. This would reduce the costs of green hydrogen production and also accommodate more renewable energy production in favorable areas. However, the costs of transporting hydrogen are high and would need to be weighed against the benefits of optimizing the input cost of electricity.

Figure 10.3.a. Hydrogen Potential from Renewable Resources by County (Levene, et. al., 2005).



Transportation costs are high because of high risk factors, the low density of the fuel, and the energy required for liquefication to increase the density for transport. The process of liquefication is needed to make transportation by truck economical. The energy for liquefication is equivalent to roughly 30% of the energy in the hydrogen itself (Burton, et. al., 2021). The transportation of hydrogen via truck or pipeline comes at the cost of need for significant additional capital and safety precautions.

Hydrogen technology currently is gaining large amounts of traction in the energy sector. The prospects of the technologies in development hold promise for significant market penetration and incorporation. As more variable production from renewable sources of energy enter the market, the need will increase for storage and ways to accommodate intermittent production. We will see not only an increase in demand for storage technologies but also a decrease in the cost of renewable energy, further decreasing the price of renewable energy, reducing the cost of green hydrogen. Some estimates put green hydrogen around $1.40/kg by the next decade (Molloy, 2019). A reduction in price to this level would put green hydrogen at a price competitive level with gray hydrogen produced from steam methane reforming.

At the moment, large infrastructure investments remain off the table for transporting hydrogen to end uses. Electricity, in the short term, will remain a cost-effective, safe, and reliable mode of transportation of energy with electrolyzers on site. As hydrogen technology and use scales up, we expect to see greater possibilities for centralized hydrogen production along with trucking and pipeline networks to consumers.

While each component of the project here has an economic evaluation, total integration of the system cost is needed. With the limited ability of this 6-person team in one semester, we fell short of being able to accomplish full integration of the system's cost. The land to site the wind and solar project will incur significant costs. Additionally, the electrical infrastructure connections to the grid, the site costs of the electrolyzer, and the refueling infrastructure will all add to the overall cost of the system. A more complete analysis of the entire system could yield insight into the local cost of hydrogen for this modeled project. From our sensitivity analysis in addition to IEA 2019 data, importance in economic considerations should be placed on electrolyzer efficiency, electrolyzer capital cost, and minimizing the levelized cost of energy for wind and solar production.

As electricity price has a large influence on the cost of hydrogen production, it is most economical to produce hydrogen when electricity prices are lowest. To take advantage of this, the hydrogen system must have an electrolyzer able to be quickly dispatched and at a low cost. Additionally, hydrogen production facilities must have sufficient storage, more than what is proposed in this project.

While this project considers the installation of wind and solar resources to provide power for electrolysis, it is most economical to produce hydrogen when the price of electricity is at a minimum. The electrolyzer could be constrained to produce only when the solar and wind resources are producing electricity. This, however, would result in higher production costs, less benefit to society, and less integration of renewable energy on the grid. If instead, the electrolyzer produces hydrogen using the makeup of electricity from the grid, regardless of power source, it will achieve lower costs of production and greater societal benefits.

Our grid consists of many generation sources, each with their own constraints. Coal provides low-cost baseload generation but takes several hours to dispatch to respond to changes in demand. Natural gas can be dispatched in a period of several minutes to respond to increases or decreases in load, but has a higher operating cost. Nuclear provides low-cost production but has almost no ability to vary its production or be dispatched. Renewable energy, namely solar and wind, produces when the sun shines and when the wind blows. Hydropower has low cost and is able to be dispatched, but is a small percentage of most grids and is limited in the amount it can be expanded. The combination of all these generation resources creates a merit-order dispatch curve, wherein the lowest marginal cost production resources are dispatched first, creating the optimal selection of resources to minimize the cost of production. Higher marginal cost resources are dispatched to meet times of high demand and/or when other lower-marginal-cost resources are offline or unable to produce electricity. Demand fluctuates diurnally with human activity, usually peaking in the evening. Demand also changes with weather patterns, when summer heatwaves or winter storms raise the demand for air conditioning and heating needs.

These market characteristics create times of low prices, when demand is low relative to production, and high prices, when demand is high relative to production. As more renewable energy generation is available on the grid, the intermittency of production will increase. When renewables are not producing, prices of electricity will be in general higher, as renewables have characteristically low/near zero marginal cost to produce electricity. When renewables are producing, they cause the price of production to fall because they displace higher-cost resources dispatched at the high-cost end of the merit-order curve. Hydrogen production from electrolysis can be turned on quickly to capture times when prices of electricity are low and shut off when prices are high. Whether low prices are due to periods of high amounts of renewable production or from dips in demand, electrolysis could be dispatched when prices are low, consuming electricity that is at a low-cost to society to produce. This low cost could be due to abundant renewables production, inability to curtail baseload generation resources when demand quickly falls off, or when demand is low and baseload resources are still producing. In any case, dispatching electrolyzers to produce during low-price periods will better accommodate fluctuations and intermittency of the grid. This will allow more variable renewable energy generation to supply the grid with power and be utilized and mitigate current challenges of the grid adjusting for ever-changing loads.

Another way of thinking about the integration with demand is in two scenarios proposed here. The wind and solar resources could be producing and demand for electricity be high, causing prices of electricity to rise. It would be best to let other loads consume the electricity from the solar and wind and curtail power to the electrolyzer while demand is high. The electrolyzer can produce at another time when demand lowers, causing the price to subside. Furthermore, there could be times when solar and wind are not producing when demand is low, like a calm, mild spring or fall night. Prices of electricity may be very low, even though wind and solar resources may not be producing. Electrolyzers could be dispatched to prevent the shutdown or curtailment of baseload generation resources that lack the ability or incur high costs in shutting down. Elecrolyzers have the potential to become a key mitigating technology on the grid, capable of being dispatched quickly to produce when prices are low and shut off when prices are high. Because of this service to the grid, there is a strong argument to be made in favor of allowing the electrolyzer to produce when prices are low rather than when it coincides directly with production from the wind and solar generation resources installed as part of this project. It is because of this argument that electricity will be taken from the grid to power the electrolysis for hydrogen generation rather than having it directly tied to the solar and wind generation in this project.

10.3 Summary

In conclusion, hydrogen technology offers another path towards decarbonizing energy. As more variable production comes onto the market, the demand will increase for technologies that accommodate discrepancies between time of production and consumption. By producing hydrogen when electricity demand is low and production is high, electrolysis can address this challenge and usher in more renewable and variable energy production in the market. Hydrogen can be stored and used later when energy consumption is needed. Hydrogen can offer pathways towards decarbonization by providing both accommodation of intermittency characteristic of greater variable production and a source of carbon-free energy. The challenge moving forward will be to find cost-effective and safe ways of storing hydrogen over long amounts of time to realize this potential.

Incorporating hydrogen production at the ChainWorks plant could serve the Ithaca area by providing a hydrogen refueling station, a reliable source of carbon-free fuel for FCEVs, and energy storage for the grid. Hydrogen technology is in its infancy stage of development. Incorporating hydrogen technology at ChainWorks would provide valuable insight into future development of hydrogen technology. Early adoption of hydrogen technology at ChainWorks would be a starting point for the Ithaca area in including hydrogen in the energy sector. This would provide exposure to technology, learning opportunities, and industry insight for future areas of improvement.

11. References and Bibliography:

Bade, D. (2021). US Department of Energy announces green hydrogen cost-cutting goal. Retrieved 28 November 2021, from https://ieefa.org/us-department-of-energy-announces-green-hydrogen-cost-cutting-goal/https://ieefa.org/us-department-of-energy-announces-green-hydrogen-cost-cutting-goal/

Burton, N., Padilla, R., Rose, A., & Habibullah, H. (2021). Increasing the efficiency of hydrogen production from solar powered water electrolysis. *Renewable And Sustainable Energy Reviews*, *135*, 110255. doi: 10.1016/j.rser.2020.110255

California Fuel Cell Partnership. (2013). *A Road Map for Fuel Cell Electric Buses in California*. Retrieved from http://cafcp.org/sites/default/files/A%20Roadmap%20for%20Fuel%20Cell%20Electric%20Buses%20in%20California.pdf

Chen, J. (2018). Lost in Transmission: World's Biggest Machine Needs Update. Retrieved 29 November 2021, from https://www.nrdc.org/experts/jennifer-chen/lost-transmission-worlds-biggest-machine-needs-update

International Energy Agency. (2019). *The Future of Hydrogen: Seizing today's opportunities*. OECD Publications Centre: OECD Publications Centre. Retrieved from https://resolver.ebscohost.com/Redirect/PRL?EPPackageLocationID=3949.22741035.49134173&epcustomerid=s9001366

Nicholas MA, Ogden J. Detailed analysis of urban station siting for California hydrogen highway network [Internet] Transp Res Rec J Transp Res Board 2006 Jan 1 [cited 2020 Jun 29];1983(1):121-8. Available from: http:// journals.sagepub.com/doi/10.1177/0361198106198300117.

National Research Council. Transitions to alternative transportation technologies-A focus on hydrogen. In: Transitions to alternative transportation technologies-A focus on hydrogen. National Academies Press; 2008. p. 1-126.

Lin Z, Chen C-W, Ogden J, Fan Y. The least-cost hydrogen for Southern Cal- ifornia. Int J Hydrogen Energy 2008;33(12).

Nicholas MA, Handy SL, Sperling D. Using geographic information systems to evaluate siting and networks of hydrogen stations. Transp res rec J transp res board [Internet]. 2004 Jan 1 [cited 2020 Jun 23];1880(1):126-34. Available from: http://journals.sagepub.com/doi/10.3141/1880-15.

Lin Z, Ogden J, Fan Y, Chen C-W. The fuel-travel-back approach to hydrogen station siting. Int J Hydrogen Energy 2008;33(12).

Kim JG, Kuby M. The deviation-flow refueling location model for optimizing a network of refueling stations. Int J Hydrogen Energy 2012 Mar 1;37(6):5406-20.

Zhao Q, Kelley SB, Xiao F, Kuby MJ. A multi-scale framework for fuel station location: from highways to street intersections. Transport Res Transport Environ 2019 Sep 1;74:48-64.

Ogden J, Nicholas M. Analysis of a “cluster” strategy for introducing hydrogen vehicles in Southern California. Energy Pol 2011 Apr 1;39(4):1923-38.

Kuby M, Lines L, Schultz R, Xie Z, Kim JG, Lim S. Optimization of hydrogen stations in Florida using the flow-refueling location model. Int J Hydrogen Energy 2009 Aug 1;34(15):6045-64.

StephensRomero SD, Brown TM, Kang JE, Recker WW, Samuelsen GS. Systematic planning to optimize investments in hydrogen infrastructure deployment. Int J Hydrogen Energy 2010 May 1;35(10):4652-67.

Melaina MW. Initiating hydrogen infrastructures: preliminary analysis of a sufficient number of initial hydrogen stations in the US. In: International journal of hydrogen energy. Pergamon; 2003. p. 743e55.

Nicholas MA. Driving demand: what can gasoline refueling patterns tell us about planning an alternative fuel network? J Transport Geogr 2010 Nov1;18(6):738e49.

Pacific Northwest National Laboratory (PNNL). H2 tools: international hydrogen fueling stations [Internet], [cited 2020 Sep 5]. Available from: https://h2tools.org/hyarc/hydrogen-data/international-hydrogen-fueling- stations; 2020.

Alternative Fuels Data Center (AFDC). Hydrogen fueling stations [Internet]. [cited 2020 Sep 5]. Available from: https://afdc.energy.gov/fuels/hydrogen_ stations.html.

International Energy Agency. (2019). The Future of Hydrogen: Seizing today’s opportunities. OECD Publications Centre: OECD Publications Centre. Retrieved from https://resolver.ebscohost.com/Redirect/PRL?EPPackageLocationID=3949.22741035.49134173&epcustomerid=s9001366

Godula-Jopek, A., Jehle, W., & Wellnitz Joӧ̈rg. (2012). Hydrogen storage technologies: new materials, transport, and infrastructure. Weinheim: Wiley-VCH. Retrieved from https://resolver.ebscohost.com/Redirect/PRL?EPPackageLocationID=2106155.1381744.21618751&epcustomerid=s9001366

Khan, U., Yamamoto, T., & Sato, H. (2021). An insight into potential early adopters of hydrogen fuel-cell vehicles in Japan. International Journal of Hydrogen Energy, 46(18), 10589–10607. https://doi-org.proxy.library.cornell.edu/10.1016/j.ijhydene.2020.12.173

Levelized Cost Of Energy, Levelized Cost Of Storage, and Levelized Cost Of Hydrogen. (2021). Retrieved 1 December 2021, from https://www.lazard.com/perspective/levelized-cost-of-energy-levelized-cost-of-storage-and-levelized-cost-of-hydrogen/

Levene, J., Mann, M., Margolis, R., & Milbrandt, A. (2005). An Analysis of Hydrogen Production from Renewable Electricity Sources. In *ISES 2005 Solar World Congress*. Orlando, FL: NREL. Retrieved from https://www.nrel.gov/docs/fy05osti/37612.pdf

Liquid Hydrogen Delivery. (2021). Retrieved 30 November 2021, from https://www.energy.gov/eere/fuelcells/liquid-hydrogen-delivery

National Renewable Energy Laboratory. (2021). *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2020*. Retrieved from https://www.nrel.gov/docs/fy21osti/75583.pdf

NREL. (2010). *New York Annual Average Wind Speed at 80m* [Image]. Retrieved from https://windexchange.energy.gov/maps-data/95

National Renewable Energy Laboratory. (2009). *Analyzing the Levelized Cost of Centralized and Distributed Hydrogen Production Using the H2A Production Model, Version 2*. Retrieved from https://www.nrel.gov/docs/fy09osti/46267.pdf

Nel ASA: Receives contract for a 1.25 MW containerized PEM electrolyzer for DOE H2@Scale project in the US | Nel Hydrogen. (2021). Retrieved 29 November 2021, from https://nelhydrogen.com/press-release/nel-asa-receives-contract-for-a-1-25-mw-containerized-pem-electrolyzer-for-doe-h2scale-project-in-the-us/

Molloy, P. (2019). Run on Less with Hydrogen Fuel Cells - RMI. Retrieved 29 November 2021, from https://rmi.org/run-on-less-with-hydrogen-fuel-cells/

Tompkins Consolidated Area Transit. (2018). *2017 Annual Report*. Retrieved from https://tcatbus.com/wp-content/uploads/2018/11/TCAT-2017-Annual-Report-FINAL.pdf

van Renssen, S. (2020). The hydrogen solution?. *Nature Climate Change*, *10*(9), 799-801. doi: 10.1038/s41558-020-0891-0

Vanek, Francis M., Louis D. Albright, and Largus T. Angenent. 2012. *Energy Systems Engineering: Evaluation and Implementation*. 2nd ed. New York: McGraw-Hill Education. https://www-accessengineeringlibrary-com.proxy.library.cornell.edu/content/book/9781259585098

Vanek, F. (2021). Fenner Wind Farm Capacity Factor [Email].

NREL (2014) Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs Contract No. DE-AC36-08GO28308 https://www.nrel.gov/docs/fy14osti/58564.pdf

Godula-Jopek, A., Jehle, W., & Wellnitz Jörg. (2012). Hydrogen storage technologies: new materials, transport, and infrastructure. Weinheim: Wiley-VCH. Retrieved from https://resolver.ebscohost.com/Redirect/PRL?EPPackageLocationID=2106155.1381744.21618751&epcustomerid=s9001366

Melaina, M. W., & Eichman, J. (2015). Hydrogen energy storage: grid and transportation services. Golden, Colorado: National Renewable Energy Laboratory. Retrieved from https://purl.fdlp.gov/GPO/gpo55609

CaFCP road map for procurement of fuel cell buses in California. (2019). Fuel Cells Bulletin, 2019(10), 10. https://doi-org.proxy.library.cornell.edu/10.1016/S1464-2859(19)30425-0

AC Transit analysis of zero-emission bus tech. (2021). Fuel Cells Bulletin, 2021(8), 3. https://doi-org.proxy.library.cornell.edu/10.1016/S1464-2859(21)00422-3

Li, J., Youn, E., Ramteke, A., McRobie, J., Hansen, E., Hall, C., Kratschmar, K., Prakash, A., Conrad, K., & Ku, A. Y. (2021). Liquid pump-enabled hydrogen refueling system for heavy duty fuel cell vehicles: Fuel cell bus refueling demonstration at Stark Area Regional Transit Authority (SARTA). International Journal of Hydrogen Energy, 46(78), 38575–38587. https://doi-org.proxy.library.cornell.edu/10.1016/j.ijhydene.2021.09.112

T. Lipman, J. Edwards, D. Kammen, Fuel cell system economics: comparing the costs of generating power with stationary and motor vehicle pem fuel cell systems, Energy Policy 32 (1) (2004) 101–125.

A. V. Wijk, L. Verhoef, Our car as power plant, Delft University Press, 2014.

A. Fernandes, T. Woudstra, A. V. Wijk, L. Verhoef, P. V. Aravind, Fuel cell electric vehicle as a power plant and SOFC as a natural gas reformer: An exergy analysis of different system designs, Applied Energy 173 (2016) 13–28.

Burton et al. (2020). Increasing the efficiency of hydrogen production from solar powered water electrolysis. *Renewable And Sustainable Energy Reviews,*.

IEA. (2019). *The Future of Hydrogen: Seizing today's opportunities.* Retrieved from OECD Publications Centrer: https://resolver.ebscohost.com/Redirect/PRL?EPPackageLocationID=3949.22741035.49134173&epcustomerid=s9001366

USDOE. (2020). *Hydrogen Strategy, Enabling a Low-Carbon Economy*. Retrieved from http://chrome-extension/efaidnbmnnnibpcajpcglclefindmkaj/viewer.html?pdfurl=https%3A%2F%2Fwww.energy.gov%2Fsites%2Fprod%2Ffiles%2F2020%2F07%2Ff76%2FUSDOE_FE_Hydrogen_Strategy_July2020.pdf&clen=3778026&chunk=true

Vanek. (2021). *Hydrogen at Cainworks.* Ithaca: Cornell University.

Wikipedia. (n.d.). Retrieved from wikipedia: wikipedia

Zeng et al. (2009). Recent progress in alkaline water electrolysis for hydrogen production and applications. *Progress In Energy And Combustion Science*.

12. Appendix

Appendix A

Wind Prospecting Location: Ithaca Area

Bin	Bin Low	Wind Speed U Bin Center m/s	Bin Max m/s	Power Curve 1.7-MW Power kW	Rayleigh Distribution Probability F(U)	Bin Probabilit	Annual production kWh/yr
					0		
0	0	0.5	0.75	0	0.011	0.011	0
1	0.75	1	1.25	0	0.031	0.020	0
2	1.25	1.5	1.75	0	0.059	0.029	0
3	1.75	2	2.25	0	0.096	0.037	0
4	2.25	2.5	2.75	0	0.140	0.044	0
5	2.75	3	3.25	10	0.190	0.050	4377
6	3.25	3.5	3.75	29	0.245	0.055	13880
7	3.75	4	4.25	72	0.303	0.058	36546
8	4.25	4.5	4.75	124	0.363	0.060	65055
9	4.75	5	5.25	216	0.423	0.061	114537
10	5.25	5.5	5.75	319	0.483	0.060	167578
11	5.75	6	6.25	432	0.541	0.058	220756
12	6.25	6.5	6.75	554	0.597	0.056	270760
13	6.75	7	7.25	700	0.650	0.053	322041
14	7.25	7.5	7.75	865	0.698	0.049	368993
15	7.75	8	8.25	1063	0.743	0.045	414439
16	8.25	8.5	8.75	1240	0.783	0.040	435757
17	8.75	9	9.25	1440	0.819	0.036	450035
18	9.25	9.5	9.75	1565	0.850	0.031	429326
19	9.75	10	10.25	1625	0.877	0.027	386350
20	10.25	10.5	10.75	1655	0.900	0.023	336794
21	10.75	11	11.25	1675	0.920	0.020	288208
22	11.25	11.5	11.75	1692	0.936	0.016	243213
23	11.75	12	12.25	1700	0.950	0.014	201735
24	12.25	12.5	12.75	1700	0.961	0.011	164605
25	12.75	13	13.25	1700	0.970	0.009	132763
26	13.25	13.5	13.75	1700	0.977	0.007	105863
27	13.75	14	14.25	1700	0.983	0.006	83461
28	14.25	14.5	14.75	1700	0.987	0.004	65063
29	14.75	15	15.25	1700	0.990	0.003	50159
30	15.25	15.5	15.75	1700	0.993	0.003	38242
31	15.75	16	16.25	1700	0.995	0.002	28838
32	16.25	16.5	16.75	1700	0.996	0.001	21509
33	16.75	17	17.25	1700	0.997	0.001	15869
34	17.25	17.5	17.75	1700	0.998	0.001	11582
35	17.75	18	18.25	1700	0.999	0.001	8362
36	18.25	18.5	18.75	1700	0.999	0.000	5973
37	18.75	19	19.25	1700	0.999	0.000	4221
38	19.25	19.5	19.75	1700	1.000	0.000	2951
39	19.75	20	20.25	1700	1.000	0.000	2042
40	20.25	20.5	20.75	1700	1.000	0.000	1398
41	20.75	21	21.25	1700	1.000	0.000	947
42	21.25	21.5	21.75	1700	1.000	0.000	635

Rated Capacity 1700 kW

Avg wind : U-avg 6 m/s @ 80m 80

Total Production 5514862 kWh/yr

Capacity Factor 0.37032

correction alpha 0.2

Avg wind : U-avg 6.27 m/s @ 100 100

Annual Production from 1, 1700kW turbine 5.51486 GWh/yr

Theoretical limit of p 14892000 kWh

Conversions

8760 hrs/yr

Appendix B

Solar Production											
3 MW array											
19% efficiency											
14.08% system losses				Wind Production			Total Annual Production			Transmission	
				1, 1.7 MW Turbine			10.49962	GWh/yr		95%	efficiency
Month	Tilt Angle	Production		6.0 m/s @ 80 m						(Chen, 2018)	
	degrees	kWh/Month									
Jan	56.3	282066		Annual Production							
Feb	56.3	348427		5.515	GWh/yr					9.974642	GWh/yr
Mar	56.3	453563								Arrives at Electrolyzer	
Apr	18.4	496247									
May	18.4	531991									
Jun	18.4	503247									
Jul	18.4	538324									
Aug	18.4	518814									
Sep	56.3	455152									
Oct	56.3	353381									
Nov	56.3	272755									
Dec	56.3	230656									
Total		4,984,623									
4 MW array											
Annual Production		4,984,623	kWh/yr								
		4.984623	GWh/yr								

Electrolysis			Applications												
Solid Oxide			Fuel Station			Buses			Toyota Mirai			Return to Grid			
65%	efficiency		consumption			(NREL, 2021)						via Solid Oxide Electrolyzer			
1.25 MW capacity			1000	kg/day		7.95	miles/kg		402	miles range		60%	efficiency		
						8.99	mpgde		5	kg tank					
6.483517	GWh/yr		53.3%	production of 1 fuel s		Provides			80.4	miles/kg		3.89011	GWh/yr		
Output of Electrolyzer						1546319	miles/yr					95%	transmission losses		
						TCAT 2017 Consumption			13500	miles/yr		3.695605	GWh/yr		
Energy Density of Hydrogen						1579450	miles/yr		167.9104	kg/yr		Usable electricity at consumption sites			
120	MJ/kg					97.9%	of TCAT demand		1158	cars		37.1%	round trip efficiency		
(Molloy, 2019)								without considering fuel cell vs ICE efficiencies							
0.033333	MWh/kg					(California Fuel Cell Partnership, 2013)									
194505.5	kg H2/yr					30	kg/day								
Output of Electrolyzer						17.8	buses								
532.8918	kg H2/day														
						130	miles/day								
Electrolyzer Capacity						47450	miles/yr								
30	MWh/day					5968.553	kg/yr								
900	kg/day					32.58838	buses								
Utilization															
59.2%															

Appendix C

Sensitivity Analysis Tabulation

	% change in output				
% Deviation from Base Values	Electrolysis Efficiency	Forward and Reverse Electrolysis Efficiency	Solar Production	Wind Production	Transmission
0.6923	0.6923	0.4615	0.8512	0.8411	
0.7692	0.7692	0.5769	0.8884	0.8808	
0.8462	0.8462	0.7051	0.9256	0.9206	0.8461
0.9231	0.9231	0.8462	0.9628	0.9603	0.9231
1	1	1	1	1	1
1.0769	1.0769	1.1667	1.0372	1.0397	1.0769
1.1538	1.1538	1.3462	1.0744	1.0794	
1.2308	1.2308	1.5385	1.1116	1.1192	
1.3077	1.3077	1.7436	1.1488	1.1589	

a. Overall energy consumption where hydrogen might have an advantage market in China, India, and the US.

b. Evaluating energy demand as per different modes of transport

c. Hydrogen generation/production methods

Electrolysis using renewable energy - evaluate renewable energy production

Thermochemical reactions

d. Hydrogen transportation

By truck

By Pipeline

Transport electricity and generate hydrogen on site

Optimizing hydrogen transport

Issues with Hydrogen storage and transport

e. Hydrogen fuel cells and their types.

Fuel cells

In internal combustion engines

f. Applications

Forklifts and other logistics

Long-distance trucking

Trucking situation in China and India as well as USA

g. Deployment of hydrogen refueling infrastructure

Challenges

Policy influences

Relation between refueling infrastructure and the hydrogen fuel cell vehicle market

In photolytic biological systems, microorganisms—such as green microalgae or cyanobacteria—use sunlight to split water into oxygen and hydrogen ions. The hydrogen ions can be combined through direct or indirect routes and released as hydrogen gas. Challenges for this pathway include low rates of hydrogen production and the fact that splitting water also produces oxygen, which quickly inhibits the hydrogen production reaction and can be a safety issue when mixed with hydrogen in certain concentrations. Researchers are working to develop methods to allow the microbes to produce hydrogen for longer periods of time and to increase the rate of hydrogen production.

Some photosynthetic microbes use sunlight as the driver to break down organic matter, releasing hydrogen. This is known as photo fermentative hydrogen production. Some of the major challenges of this pathway include a very low hydrogen production rate and low solar-to-hydrogen efficiency, making it a commercially unviable pathway for hydrogen production currently.

Researchers are looking at ways to make the microbes better at collecting and using energy to make more available for hydrogen production, and to change their normal biological pathways to increase the rate of hydrogen production.

Why Is This Pathway Being Considered?

In the long term, photobiological production technologies may provide economical hydrogen production from sunlight with low- to net-zero carbon emissions. The algae and bacteria could be grown in water that cannot be used for drinking or for agriculture and could potentially even use wastewater.

3.4 How much energy is wasted in generating hydrogen?

Efficiency of production methods is as follows:

Technology	Feed stock	Efficiency	Maturity	Reference
Steam reforming	Hydrocarbons	70–85%[a]	Commercial	[31]
Partial oxidation	Hydrocarbons	60–75%[a]	Commercial	[31]
Autothermal reforming	Hydrocarbons	60–75%[a]	Near term	[31]
Plasma reforming	Hydrocarbons	9–85%[b]	Long term	[74]
Aqueous phase reforming	Carbohydrates	35–55%[a]	Med. term	[99]
Ammonia reforming	Ammonia	NA	Near term	
Biomass gasification	Biomass	35–50%[a]	Commercial	[9], [20], [127]
Photolysis	Sunlight + water	0.5%[c]	Long term	[161]
Dark fermentation	Biomass	60–80%[d]	Long term	[9], [135]
Photo fermentation	Biomass + sunlight	0.1%[e]	Long term	[9], [20]
Microbial electrolysis cells	Biomass + electricity	78%[f]	Long term	[162]
Alkaline electrolyzer	H_2O + electricity	50–60%[g]	Commercial	[20], [159]
PEM electrolyzer	H_2O + electricity	55–70%[g]	Near term	[20], [159]
Solid oxide electrolysis cells	H_2O + electricity + heat	40–60%[h]	Med. Term	[127]
Thermochemical water splitting	H_2O + heat	NA	Long term	
Photoelectrochemical water splitting	H_2O + sunlight	12.4%[i]	Long term	[159], [186]

https://www.sciencedirect.com/science/article/pii/S0920586108004100?casa_token=Jf_4VPpfmHIAAAA A:HiTpf5Mii_QvqM30lZpYoDuk-T8ebMUOK_7r0PO4CD-oSOdZdgNFiUdrwNMn5BbbggVjfaFs

The global thermal and exergy efficiencies of the base-case system are 66.7% and 62.7%, respectively. Of the 37.3% of exergy not utilized within the system (un-used exergy), 81% is destroyed within the system and 19% exits in the exhaust stream. https://www.sciencedirect.com/science/article/pii/S036031990700482X?casa_token=1LH8CD1Uqb8A AAAA:w8JqI5xCH91f8MIM4jGdjYzPU-9wILJuV7R7iccKcLnzmguygHh0MG_75xgEGxHJCkNNFWxw

References:

1. https://www.eia.gov/energyexplained/hydrogen/

2. https://www.energy.gov/eere/fuelcells/hydrogen-resources

3. https://www.nrel.gov/research/eds-hydrogen.html

4. https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming

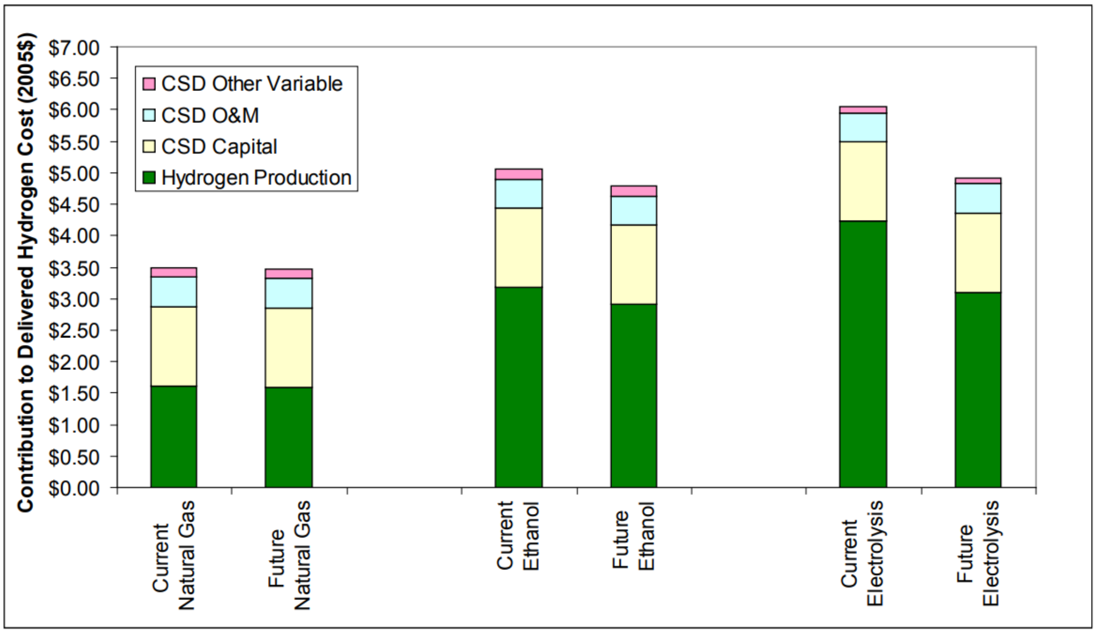


Figure 3: Forecourt: Contributions to Delivered Levelized Hydrogen Cost [6]

Figure 3 shows the CSD cost of distributed production. The total CSD cost for distributed production with electrolysis method is about $2 which is similar with cost by using other distributed technologies.

The CSD cost of centralized production could be roughly estimated by using vehicle data of Ithaca with a hypothesis of 5% market penetration.

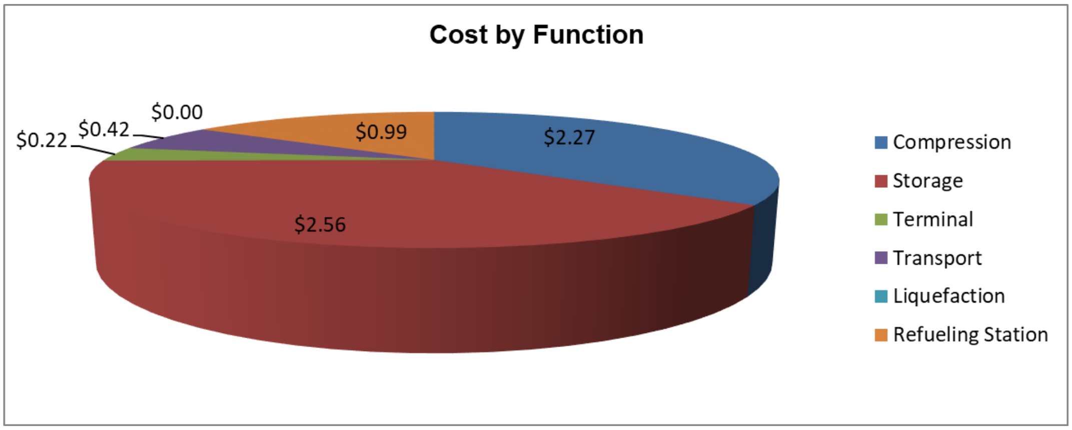


Figure 4. Cost by function of gas refueling station

Cost by Function $/kg						
	Compression	**Storage**	**Terminal**	**Transport**	**Liquefaction**	**Refueling Station**
Capital	$1.2475	$2.0643	$0.1206	$0.0942	$0.0000	$0.6083
Other O&M	$0.6918	$0.4911	$0.0994	$0.2334	$0.0000	$0.3118
Energy/Fuel	$0.3355	$0.0000	$0.0000	$0.0878	$0.0000	$0.0682
Total Cost [$/kg]	$2.2748	$2.5554	$0.2200	$0.4154	$0.0000	$0.9882

Table 2.

The total CSD cost in centralized case except from fuel cost is about $4.8 from this estimation by using Hydrogen Delivery Scenario Analysis Model with gas hydrogen refueling stations (capacity: 1000 kg/day, 700bar). The CSD cost in this case is much larger than that of distributed production which is $2.

Thus, according to the estimation results, the advantage of distributed production on the CSD cost is apparent in compassion with centralized production.

4.3.4 Transportation cost in a centralized case

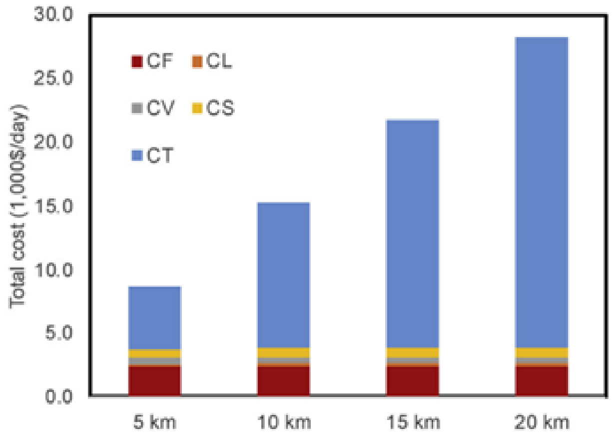


Figure 5. Changes in the total daily cost with respect to the distance between the centralized, SMR-based production site and the stations. (CF: fixed cost, CL: Cost of land use in a given period, CV: variable cost, CS: Compression, storage and dispensing cost, CT: Transportation cost) [5]

The results (Fig. 5) clearly indicate that the transportation cost (CT) dominates when H2 is supplied from the centralized, SMR-based production system to the stations that are kilometers away. It is already responsible for more than half of the total costs when the stations are 5.0 km away. In contrast, the proportion of the cost for land use (CL) is less than 2%, at least for the set of parameters used in this study. The other types of costs remain constant with respect to the transportation distance.

The high relevance between transportation cost and distance shows the disadvantage of centralized production especially when there is long distance between refueling stations and production center. In comparison, the transportation cost is almost zero for distributed technologies.

4.3.5 Feasibility of distributed production by renewable energy

Current electrolysis units that could be used for transportation fuel have production rates that range from 1 kg of hydrogen per day to 1000 kg of hydrogen per day. The 1kg/day electrolysis unit could be used as home refueling. The 1000 kg/day unit would fill approximately 170 cars per day and would be considered a small filling station. Two such units operating at 75% capacity factor would provide 1500 kg/day of hydrogen and fuel 250 cars per day. This is one of the standard system sizes analyzed by the H2A team. [7]

The power requirements are significant for electrolysis systems. A boundary analysis determines whether or not a distributed renewable energy system could independently provide the electricity needed for producing 1500 kg of hydrogen per day at the filling station. Such a station would require 3.5 MW of power, or 31 GWh of electricity annually. If the energy source is a PV solar farm, a fueling station of this size would require at least 175,000 square meters (43.2 acres) of PV cells. A distributed wind system would require 11 MW of installed turbine capacity to meet the entire energy needs of this hydrogen fueling station. In this case, a station providing 1500 kg of hydrogen would require a wind farm of approximately 2.2 km2 (540 acres). [7]

According to the estimation of scale needed for a solar farm or a wind farm to provide energy for a standard refueling station, it seems impossible to have such large-scale farms in a densely populated region. However, there are also other scenarios could provide possibility including fueling stations fed from renewable electricity generation decoupled from the filling station, renewable on-site electricity generation and grid electricity blend, remote renewable energy generation blended with on-site renewable energy supplies or using solar energy in conjunction with high temperature electrolysis.

Reference list

[1] Well-to-wheels emissions, costs, and feedstock potentials for light-duty hydrogen fuel cell vehicles in China in 2017 and 2030

[2] International Energy Agency. (2019). *The Future of Hydrogen: Seizing today's opportunities.* OECD Publications Centre: OECD Publications Centre. Retrieved from https://resolver.ebscohost.com/Redirect/PRL?EPPackageLocationID=3949.22741035.49134173&epcustomerid=s9001366

[3] Godula-Jopek, A., Jehle, W., & Wellnitz Jorg̈. (2012). *Hydrogen storage technologies: new materials, transport, and infrastructure.* Weinheim: Wiley-VCH. Retrieved from https://resolver.ebscohost.com/Redirect/PRL?EPPackageLocationID=2106155.1381744.21618751&epcustomerid=s9001366

[4] Fletcher, J., & Callaghan, V. (2006). Distributed Hydrogen Production from Natural Gas: Independent Review. Washington, D.C.: United States. Dept. of Energy. Retrieved from http://www.osti.gov/servlets/purl/893444-O3UfPf/

[5] Park, K., & Koo, J. (2020). Optimal design of the distributed H2 production system with cost and safety considerations. International Journal of Hydrogen Energy, 45(59), 34316–34325. https://doi-org.proxy.library.cornell.edu/10.1016/j.ijhydene.2020.01.165

[6] Ramsden, T., Steward, D., & Zuboy, J. (2009). Analyzing the levelized cost of centralized and distributed hydrogen production using the H2A Production Model, Version 2. Golden, Colo.: National Renewable Energy Laboratory. Retrieved from https://purl.fdlp.gov/GPO/gpo23813

[7] Mann, M. K., Margolis, R. M., Milbrandt, A., & Levene, J. I. (2005). Analysis of Hydrogen Production from Renewable Electricity Sources: Preprint. Washington, D.C.: United States. Dept. of Energy. Retrieved from http://www.osti.gov/servlets/purl/15020344-qh3Dqm/

5. Hydrogen fuel cells and their types

5.1 Fuel cells

A fuel cell (FC) has a direct analogy to an internal combustion engine (ICE). An ICE converts chemical energy stored in the fuel supplied to the engine to produce rotational mechanical energy. The rotational energy produced is then either used to propel a vehicle or focused through a generator and converted into electrical energy. An FC acts much in the same way as an ICE in that chemical energy is directly converted into electrical energy in the FC, but in an environmentally friendly process (Manoharan, 2019).

In other words, fuel cell means a device that can convert chemical energy into electricity directly. Normally it has three major parts: a fuel electrode (anode), an oxidant electrode (cathode), and an electrolyte.

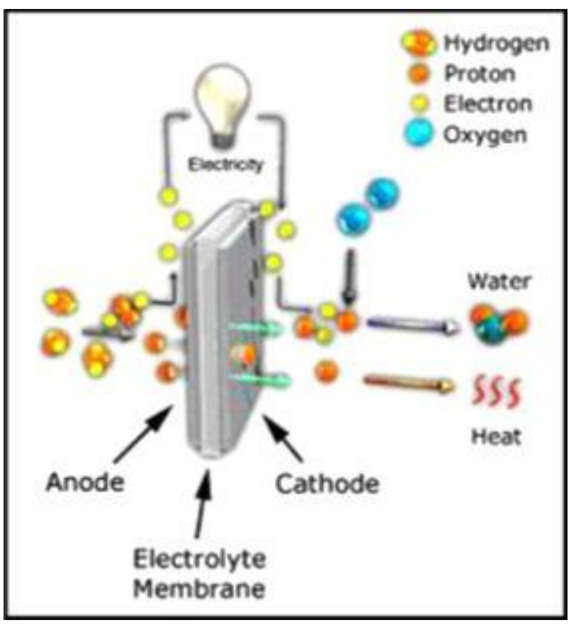


Fig. a. The mechanism of hydrogen fuel cell (Sharaf,)

Besides, the chemical reaction inside of the fuel is quite and stable. It does not require a complex mechanical system to transfer the energy. Does not have any moving parts and don't make any noise.

The major exhaust for hydrogen fuel cell is water. Compare with the internal combustion engine, it decreases the energy loss energy conversation from chemical to mechanical then convert to electrical energy. Base on the experiment of the assessment of different fuel sources vehicle.

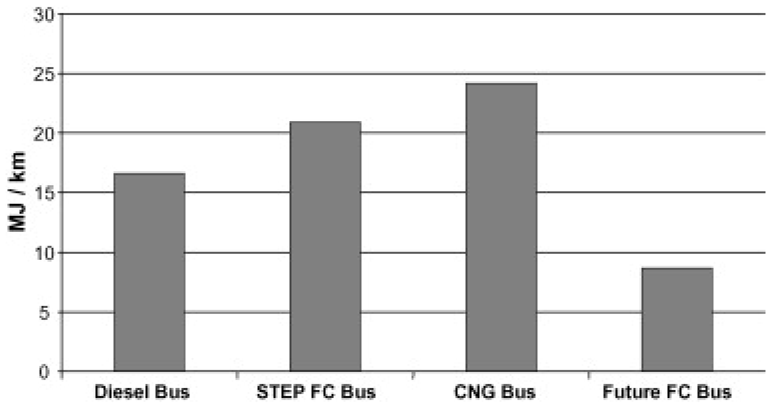


Fig. b. Comparison of vehicle energy efficiency for diesel, natural gas, hydrogen fuel cell, and future hydrogen fuel cell buses. (Ally, 2007).

Due to the limitation of the Carnot cycle, the average efficiency for internal combustion engine is 35%. The department of energy indicate that the average energy efficiency for fuel cell is 60%. We can see the difference of efficiency between different type fuel resources.

Ally, J., & Pryor, T. (2007, April 25). *Life-cycle assessment of diesel, natural gas and hydrogen fuel cell bus transportation systems*. Journal of Power Sources. Retrieved September 29, 2021, from https://www.sciencedirect.com/science/article/pii/S0378775307008117.

Fuel cells fact sheet - department of energy. (n.d.). Retrieved September 29, 2021, from https://www.energy.gov/sites/prod/files/2015/11/f27/fcto_fuel_cells_fact_sheet.pdf.

Manoharan, Y., Hosseini, S. E., Butler, B., Alzhahrani, H., Senior, B. T. F., Ashuri, T., & Krohn, J. (2019). Hydrogen fuel cell vehicles; current status and future prospect. *Applied Sciences*, *9*(11), 2296.

Sharaf, O. Z., & Orhan, M. F. (2014, February 13). *An overview of fuel cell technology: Fundamentals and applications*. Renewable and Sustainable Energy Reviews. Retrieved September 29, 2021, from https://www.sciencedirect.com/science/article/pii/S1364032114000227.

Types of Fuel Cells

Fig (a) Comparison of Fuel Cell Applications, Advantages, and Disadvantages

	Applications	Advantages	Disadvantages
Alkaline (AFC)	• Military • Space	• Cathode reaction faster in alkaline electrolyte, leads to high performance • Low cost components	• Sensitive to CO_2 in fuel and air • Electrolyte management
Direct Methanol (DMFC)	• Backup power • Portable power • Military	• No need for reformer (catalyst separates H2 from liquid methanol) • Low temperature	• Expensive catalysts • Low temperature waste heat
Phosphoric Acid (PAFC)	• Auxiliary power • Electric utility • Distributed generation	• Higher temperature enables CHP • Increased tolerance to fuel impurities	• Platinum catalyst • Startup time • Low current and power
Proton Exchange Membrane (PEMFC)	• Backup power • Portable power • Distributed generation • Transportation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick startup	• Expensive catalysts • Sensitive to fuel impurities • Low temperature waste heat
Molten Carbonate (MCFC)	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP	• High temperature corrosion and breakdown • Long startup time • Low power density
Solid Oxide (SOFC)	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & Combined heat, hydrogen, and powerHybrid/GT cycle	• High temperature corrosion and breakdown of cell components • High temperature operation requires long startup time and limits

(*Catalog of CHP Technologies, Section 6. Technology Characterization – Fuel Cells*, 2015)

Many different types of fuel cells are undergoing development and are available for our application. Several of the most common types of fuel cells are listed below in Fig (a) above. The fuel cells in Fig (a) are organized by operating temperatures, with lower temperatures at the top and high temperatures at the bottom. Proton exchange membrane (PEMFC), alkaline (AFC), and direct methanol (DMFC) fuel cells have lower operating temperatures making them more suitable for applications in transportation. Other fuel cells, such as phosphoric acid (PAFC), molten carbonate (MCFC), and solid oxide (SOFC) fuel cells operate at higher temperatures.

These higher temperatures allow for coupling with combined heat and power systems in stationary settings (*Catalog of CHP Technologies, Section 6. Technology Characterization – Fuel Cells*, 2015). Proton exchange membrane fuel cells also hold high potential for use in combined heat and power (CHP) systems. Adding CHP to stationary fuel cells allows the use of waste heat for hot water supply or other thermal demands. Typical electrical efficiency for many fuel cells is around 60%. CHP can boost overall efficiency to around 85% for many fuel cell types.

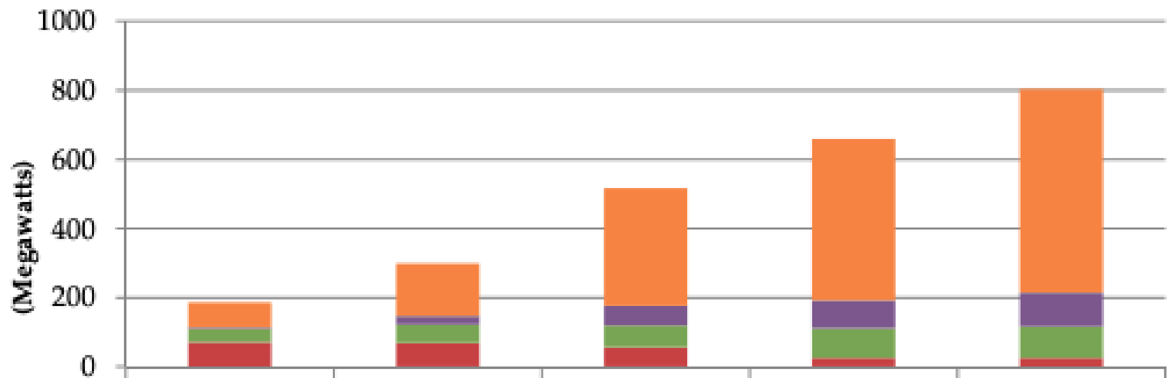
Fig (b) shows a range of operating temperatures, output capacities, and system efficiencies of fuel cells by type.

Fuel Cell Type	Operating Temperature	System Output	Efficiency	Applications
Alkaline (AFC)	90–100°C 194–212°F	10kW–100kW	60–70% electric	• Military • Space
Phosphoric Acid (PAFC)	150–200°C 302–392°F	50kW–1MW (250kW module typical)	80–85% overall with combined heat and power (CHP) (36–42% electric)	• Distributed generation
Polymer Electrolyte Membrane or Proton Exchange Membrane (PEM)*	50–100°C 122–212°F	<250kW	50–60% electric	• Back-up power • Portable power • Small distributed generation • Transportation
Molten Carbonate (MCFC)	600–700°C 1112–1292°F	<1MW (250kW module typical)	85% overall with CHP (60% electric)	• Electric utility • Large distributed generation
Solid Oxide (SOFC)	650–1000°C 1202–1832°F	5kW–3 MW	85% overall with CHP (60% electric)	• Auxiliary power • Electric utility • Large distributed generation

(*Hydrogen Fuel Cells*, 2006)

Recent studies in the fuel cell market show current installed capacities by fuel cell type, sector, and region. It is notable that proton exchange membranes fuel cells have become dominant in the market, especially in transportation (Felseghi, et al., 2019). Phosphoric acid and solid oxide fuel cells are also starting to become commercially viable.

Fig (d). Global installed fuel cell capacity by fuel cell type.

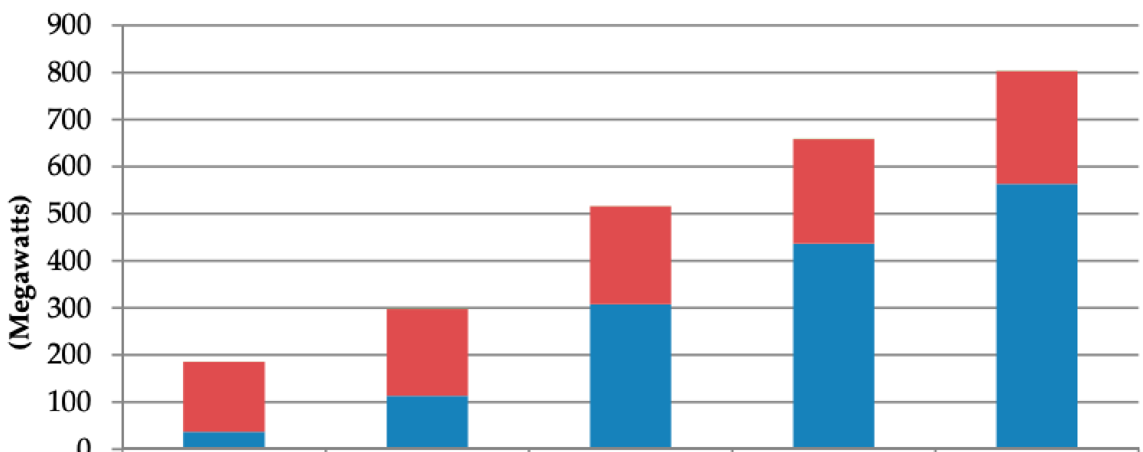


	2014	2015	2016	2017	2018
PEMFC	72.7	151.8	341	466.7	589.1
DMFC	0.2	0.2	0.2	0.3	0.4
PAFC	3.8	24	56.2	81	97.3
SOFC	38.2	53.3	62.9	85.2	91
MCFC	70.5	68.6	55.7	24.7	25.2
AFC	0.1	0.2	0.5	0.6	0.1

(Felseghi, et al., 2019).

In recent years, both stationary and transportation sectors have added capacity. However, the transportation sector has seen the majority of the growth, now comprising most of the market. Much of the stationary capacity in the market is identified by Felseghi, et al, 2019 as originating from the microsystems installed in Japan as part of a residential fuel cell program called ENE-FARM.

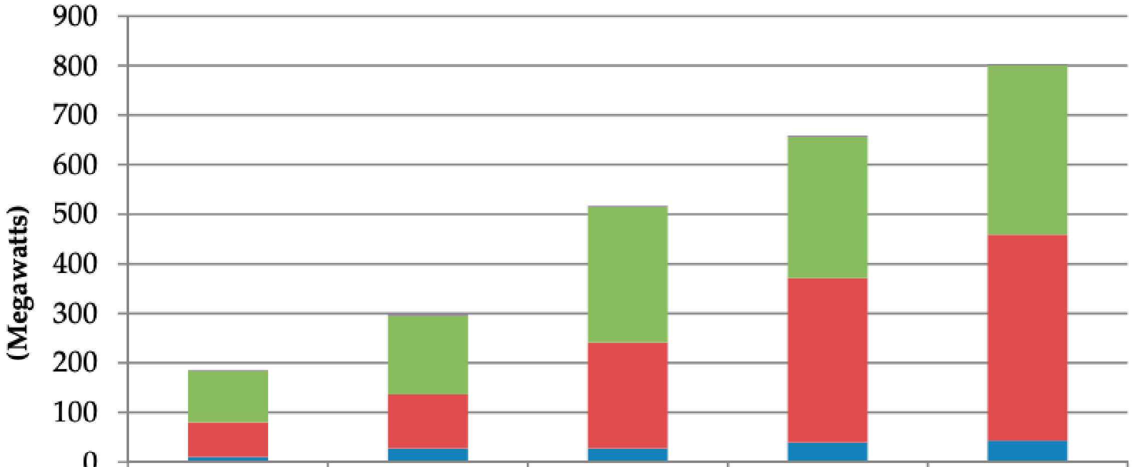
Fig (e). Global installed capacity by sector.



	2014	2015	2016	2017	2018
Portable	0.4	0.9	0.3	0.6	0.7
Stationary	147.8	183.6	209	222.3	239.8
Transport	37.2	113.6	307.2	435.7	562.6

(Felseghi, et al., 2019).

Fig (f). Global installed capacity by region.



	2014	2015	2016	2017	2018
RoW	1.2	2.3	1.7	2.1	1.4
Asia	104.5	159.7	273.8	285.8	343.3
N America	69.8	108.4	213.6	331.8	415
Europe	9.9	27.7	27.4	38.9	43.4

(Felseghi, et al., 2019).

In internal combustion engines

References

Argonne National Laboratory, U.S. Department of Energy. (2006). *Hydrogen Fuel Cells* [Ebook]. Retrieved from http://chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/viewer.html?pdfurl=https%3A%2F%2Fwww.californiahydrogen.org%2Fwp-content%2Fuploads%2Ffiles%2Fdoe_fuelcell_factsheet.pdf&clen=831145&chunk=true

Felseghi, R., Carcadea, E., Raboaca, M., Trufin, C., & Filote, C. (2019). Hydrogen Fuel Cell Technology for the Sustainable Future of Stationary Applications. *Energies*, *12*(23). doi: 10.3390/en12234593

U.S. Environmental Protection Agency Combined Heat and Power Partnership March 2015. (2015). *Catalog of CHP Technologies, Section 6. Technology Characterization – Fuel Cells* [Ebook]. Retrieved from http://chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/viewer.html?pdfurl=https%3A%2F%2Fwww.epa.gov%2Fsites%2Fdefault%2Ffiles%2F2015-07%2Fdocuments%2Fcatalog_of_chp_technologies_section_6._technology_characterization_-_fuel_cells.pdf&clen=1168607&chunk=true

References

1. Why the future of long-haul heavy trucking probably includes lots of hydrogen | Greenbiz. (2021, June 15).

2. https://www.gladstein.org/hydrogen-fuel-cell-trucks/

3. 19006_hydrogen_class8_long_haul_truck_targets

4. https://www.trucks.com/2019/03/29/nikola-motor-fuel-cell-lab/

Thomas Walker. https://www.greenbiz.com/article/why-future-long-haul-heavy-trucking-probably-includes-lots-hydrogen

6.3 Stationary uses

The stationary sector ranges from small backup power systems, to large residential, industrial and primary power systems, or for combined heat and power systems. Each of these stationary fuel cell systems provide reliable, clean and quiet power as well as improved efficiencies, resiliency, reduced emissions and lower energy costs. (1)

Fuel cells are highly efficient, typically reaching fuel to electricity efficiency of 60 percent, nearly double the efficiency of today's electric grid. Fuel cells also generate heat which, if captured, can increase overall energy efficiency to more than 90 percent. The heat produced by fuel cells can generate additional electricity through a turbine, provide heating directly to nearby buildings or facilities, and even cooling with the addition of an absorption chiller.(2)

As an example, fuel cells provided critical emergency backup power to telecommunications towers operating for hundreds of hours in both the Bahamas and the Northeast United States after Hurricane Sandy slammed the Caribbean and the East Coast in 2012. Fuel cells can offer significant cost advantages over battery-generator systems when shorter run-times of three days or less are sufficient.(1). At a local level, stationary fuel cells are used as part of uninterruptible power supply (UPS) systems, where continuous uptime is critical. Both hospitals and data centers are increasingly looking to hydrogen to meet their uninterruptible power supply needs. Recently, Microsoft made headlines with a successful test of its new hydrogen backup generators, running one data center's servers on nothing but hydrogen for two days.(3)

References:

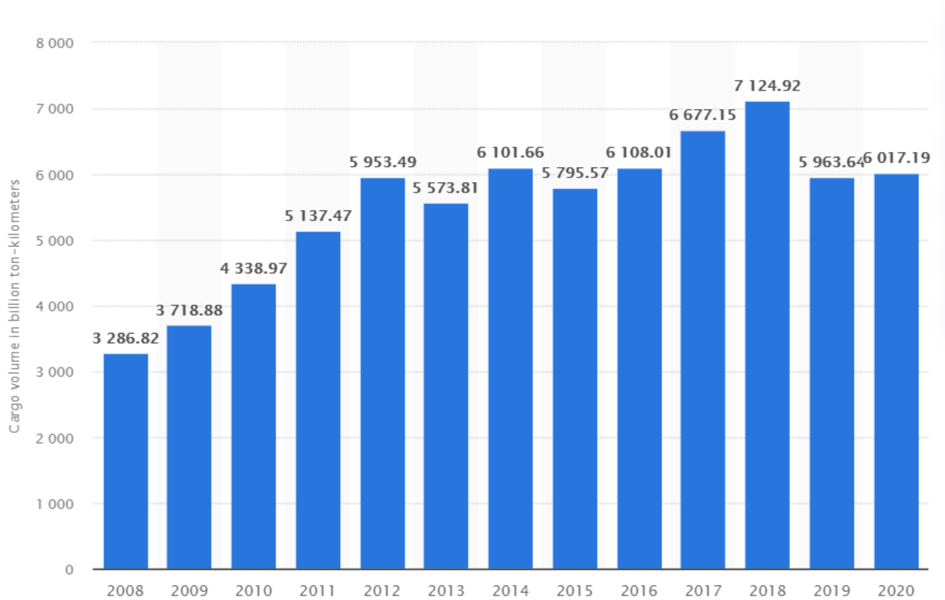
(1)http://www.chfca.ca/fuel-cells-hydrogen/hydrogen-fuel-cell-applications/

(2) https://www.fchea.org/stationary

(3)https://wha-international.com/10-hydrogen-fuel-cell-applications-you-might-not-know/

Trucking situation in China and India as well as USA

Volume of road freight traffic in China from 2008 to 2020*(in billion ton-kilometers)*



As the world's largest developing country, China has rapidly developed state-of-the-art mobile infrastructure. Its vast network of roads can transport billions of tonnes of goods each year. But China's road freight volume fell to 6 billion tonnage kilometers by 2020, the second year of decline since a peak in 2018.

References

Statista. (2021, August 5). *Volume of road freight traffic in China 2008–2020*. https://www.statista.com/statistics/275915/volume-of-road-freight-traffic-in-china/#statisticContainer

7. Deployment of hydrogen refueling infrastructure

7.1 Hydrogen Refueling Station Planning

Definition, Goal & Considerations

What is HRS Planning: consists of decisions on the technology type, number, locations and sizes (and the resulting utilization) of the stations to be deployed for meeting the hydrogen demand anticipated from a growing population of fuel cell vehicles in a given region [1-3].

Goal: to minimize the expected system cost for given constraints and to provide guidance for deployment actions.

IEA (International Energy Agency) estimates investment costs for current hydrogen refueling stations in the range of $0.6-2 million for hydrogen at a pressure of 700 bar, and $0.15-1.6 million at 350 bar.

There is considerable scope of reducing the cost of hydrogen refueling stations by:

Scaling up the station size,

Reducing the station capital cost via mass production and process development of key components such as compressors, storage and onsite electrolyzers,

Improving the utilization of the station via growing demand.

Considerations: both supply (e.g., station technology performance and cost) and demand (e.g., where and how often refueling needs will occur). Especially for new types of infrastructure technologies it is important for planning to include issues such as permitting and compliance with codes and standards to reduce the likelihood of unanticipated delays or costs.

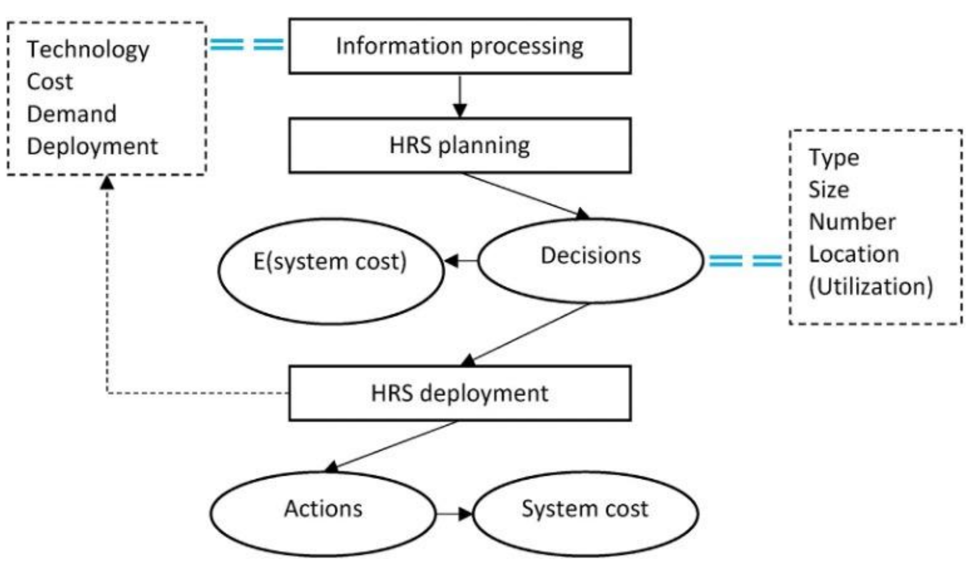


Fig.7.1. HRS Planning Framework

(Rectangle with solid borders—processes, ovals—outcomes, rect with dashes borders--data)

Significance

Lack of refueling stations is a significant problem met by the users of HFCVs. It is the main reason for people to decide to no longer use HFCVs.

Figure 7.2. Percentage of the private adopters who will replace HFCV when inquired, 'What is the reason of replacing current HFCV' [1]

Core questions & Solution

Core questions: how many refueling stations to deploy? where to locate them?

Solution for location optimization -- *P-median Model* (maximum covering location problem)

Objective: minimize the weighted average distance of refueling demand to the nearest station [4,5] and maximize refueling convenience. The smaller this weighted average distance, the more accessible the HRS network is to FCV drivers. (distance is defined to be 0 if the actual distance is within a certain limit and 1 otherwise)

Demand origins determines the type of distance weight --> Where does hydrogen refueling demand originate from?

Home and workplaces: weighted by population density [4].

Traffic flows[5,6,7]: the p-median problem can be adapted by treating hydrogen demand clusters, rather than the general traffic in the region, as demand origins [8].

Potential constraints: station capacity [8], FCV driving range [9] and land use [10].

The capacity of each located station can be estimated based on the allocated hydrogen demand. The total station cost can then be calculated. When station capacity is also a decision variable, it raises the critical issue of economies of scale. In that case, a suitable objective is minimizing the total system cost, including station costs and the monetized refueling inconvenience determined by station location and numbers. For a given total hydrogen demand, more stations mean smaller average station sizes and thus higher station costs, but less refueling inconvenience.

Exponential relationship between refueling travel time and station number:

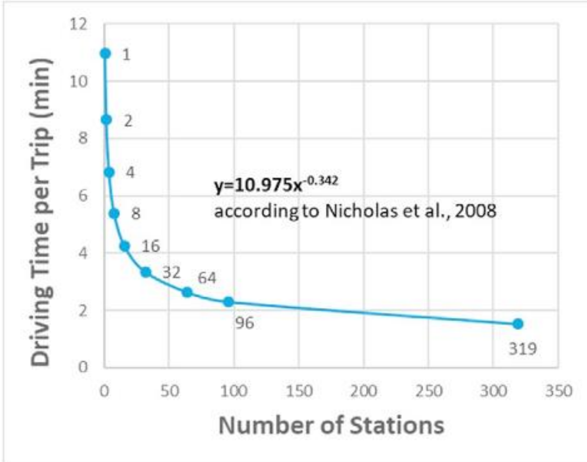


Figure 7.3(a)

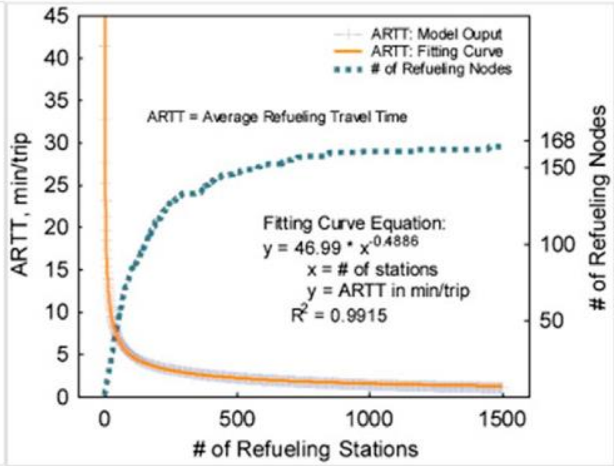


Figure 7.3(b)

7.2 Cost of refueling station

The two largest cost components are the compressor (which can be up to 60% of the total cost when the delivery pressure is 700 bar) to achieve the delivery pressure, and the storage tanks (which are relatively large due to lower hydrogen density). The actual cost of building a station varies considerably across countries, mainly as a result of different safety and permitting requirements. There are strong economies of scale. Increasing the capacity from 50 to 500 kgH2/day would be likely to reduce the specific cost (i.e. the capital cost per kg of hydrogen dispensed) by 75%. Larger capacity stations of up to a few 1 000 kgH2/day are being planned, especially for heavy-duty applications, and these offer potential for further economies of scale. There is also potential for costs to be reduced through a shift to more advanced supply options (such as very high pressure or liquid hydrogen) and through scale-up in the manufacturing of refueling station products (via mass production of components, such as the compressors). [16-17]

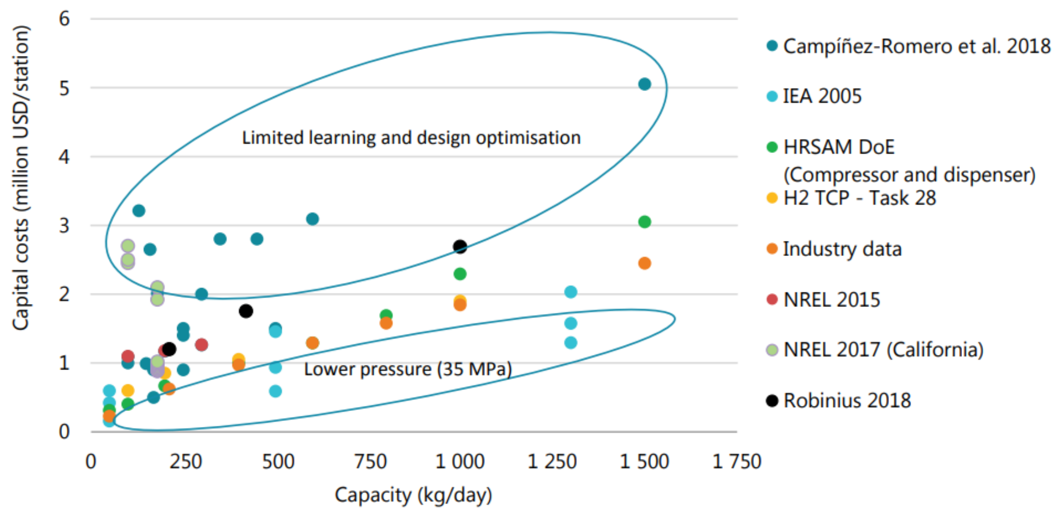


Figure 7.4. Benchmarking hydrogen refueling station capital costs as a function of capacity. [16]

The costs of providing hydrogen to FCEVs can be brought down by building larger refueling stations as long as expected hydrogen demand allows as shown in Figure 7.4. Thus, there will be scale effects in deployment of hydrogen refueling stations.

Risks related to the tension between refueling station size, the cost of hydrogen and hydrogen demand are among the barriers to rapid hydrogen uptake for transport. Small stations make more economic sense in the initial deployment phase as they are more likely to secure higher capacity utilization rates when demand for hydrogen from transport vehicles is limited, but they come at higher cost per unit of hydrogen delivered. Once sufficient demand volumes have been established, larger stations become more economic and can help reduce the cost of hydrogen for the end users. The cost of delivered hydrogen will also depend on whether the hydrogen is produced locally or delivered from centralized production facilities. [17] The cost advantages of centralized production may be outweighed by the cost of distribution to the refueling station by truck or pipeline. The cheapest option will be determined case by case.

7.3 Candidate locations for HRS

In real-world HRS planning, the candidate locations for HRS can be selected from all of the nodes on the network. It is also important to exclude locations that are impractical because of land use policies, land cost or the lack of suitable parcels of land.

Intuitively, candidate locations can be the current gas station sites [4], which can be further down selected by removal of sites that are impossible to add or be replaced by HRS equipment. Other types of candidate locations are population centers, highway entrances, inter-city long-distance trip stops, locations near early FCV drivers, [11,12].

7.4 Global status of hydrogen refueling stations and plans

The number of hydrogen refueling stations in the world is a rapidly increasing moving target. Nearly all are supported by government subsidies, typically on the order of a 50% cost share. The Pacific Northwest National Laboratory [13] and National Renewable Energy Laboratory [14] report a total of 385 active hydrogen stations, with another 167 planned to open in the next year or two. Of the 385 active stations identified by PNNL, 268 (78.4%) are open to the public.

The capacity of many stations is not available in the H2 Tools database, yet stations dispensing hydrogen at 70 MPa or both 70 and 35 MPa comprise the large majority. The international standard for on-board storage for passenger cars is 70 MPa, while buses are frequently designed to store hydrogen at 35 MPa. Considering all stations in the PNNL database (active, planned, public and private) for which delivery pressure is available, 15.5% supply at 35 MPa only, 71.1% at 70 MPa only, and 13.4% can deliver hydrogen into a vehicle at either pressure (Fig. 7.5).

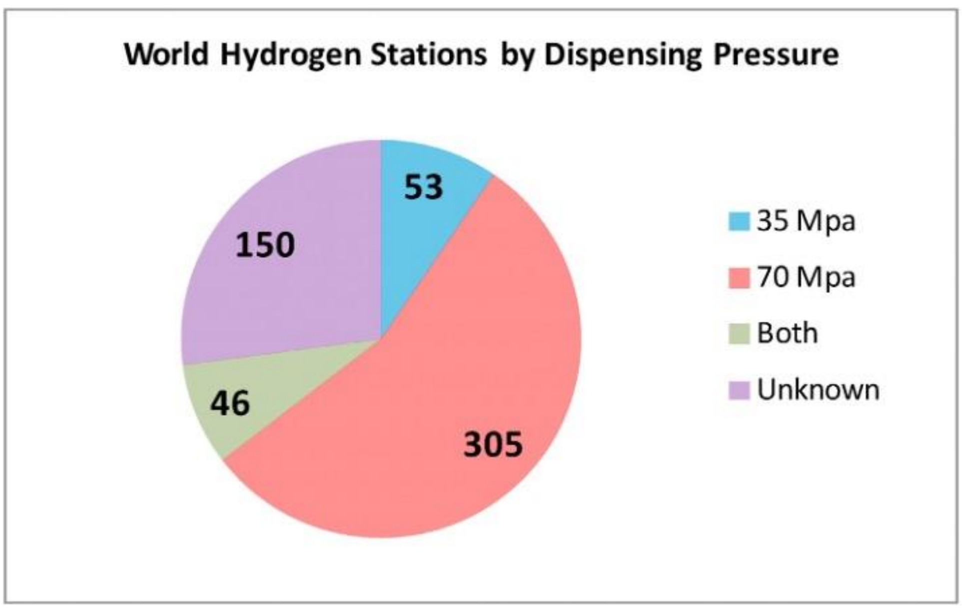


Fig. 7.5. World hydrogen stations by dispensing pressure (H2 tools, 2020).

The seven countries with the most hydrogen stations account for 82.3% of the active stations. The distribution of stations by the seven countries and the rest of the World, by status (public and private, active and planned) are shown in Fig. 7.6. Planned stations are typically expected be opened within the current year. Four fifths of the stations are open to the public while others are for the use of bus companies or otherwise restricted.

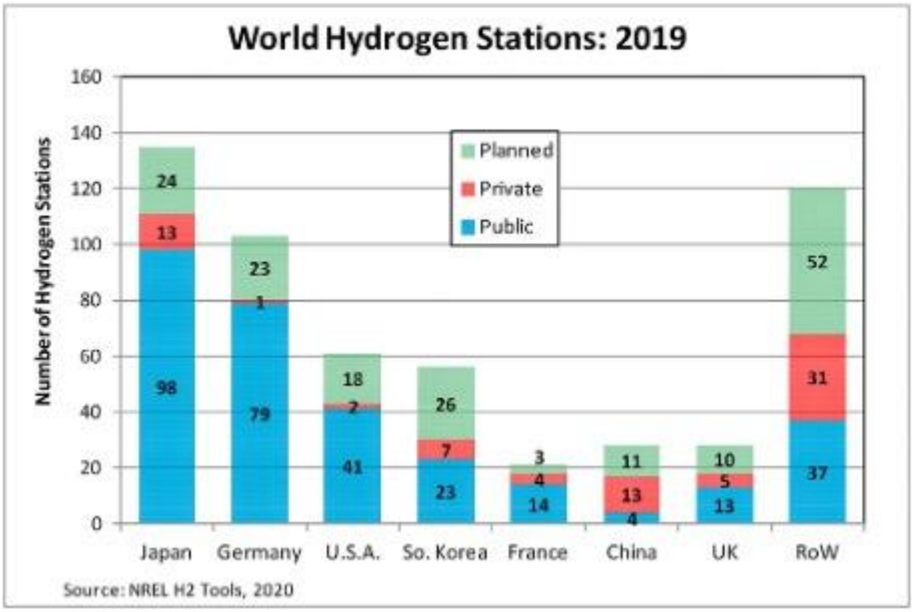


Fig. 7.6. World hydrogen stations (H2 tools, 2020).

7.5 Probable strategy

For low market penetration which might highly possible our current situation.

Ogden and Nicholas (2011) developed a station "cluster strategy" for deploying hydrogen refueling stations that was adopted by the State of California (CAFCP, 2012) [19-21]. The cluster strategy creates strategic niche markets for FCVs by locating several stations in smaller geographical areas with a high concentration of likely early adopters of FCVs. The geographical niches not only provide convenient and reliable access to subsidized stations but by spatially concentrating the adoption of a novel technology they accelerate diffusion by facilitating institutional and social learning. Concentrating demand creates the potential for station profitability at low levels of FCV market penetration.

The success of the cluster strategy is based on a more complex understanding of the need for stations in the early transition. Whereas prior studies estimated that the minimum number of hydrogen stations for creation of a mass market was 15%-20% of that of existing gasoline stations, the cluster strategy recognized that an individual FCV could accomplish more than 90%

of a conventional vehicle's annual travel if only one station were located within a few kilometers of its home base. [19] For example, well over 90% of the annual miles of travel of a typical household vehicle in California occur on days on which vehicle travel is well within the range of a FCV (Figure 7.7). In accord with this observation, a survey of FCVs in California found that they averaged 12,500 miles per year, 91% of the state average of 13,739 for 1-4-year-old conventional vehicles.

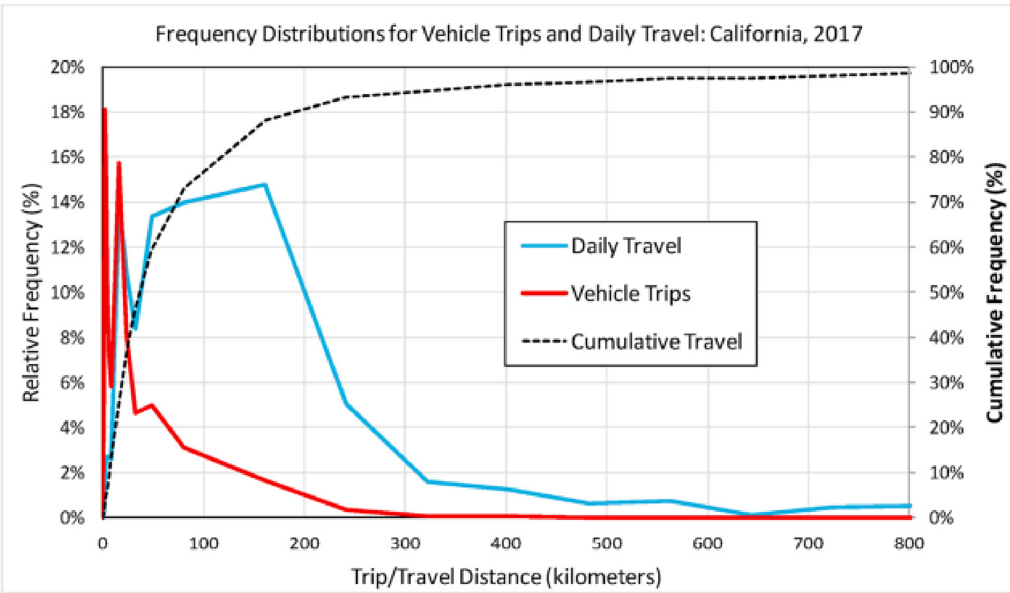


Figure 7.7. Frequency distributions for vehicle trips [19]

7.6 Modeling of deployment of refueling stations in Ithaca

Modeling by using data for Ithaca through Hydrogen Delivery Scenario Analysis Model

Market penetration is assumed to be 5%

By using gas hydrogen with 4 refueling stations (capacity: 1000 kg/day, 700bar)

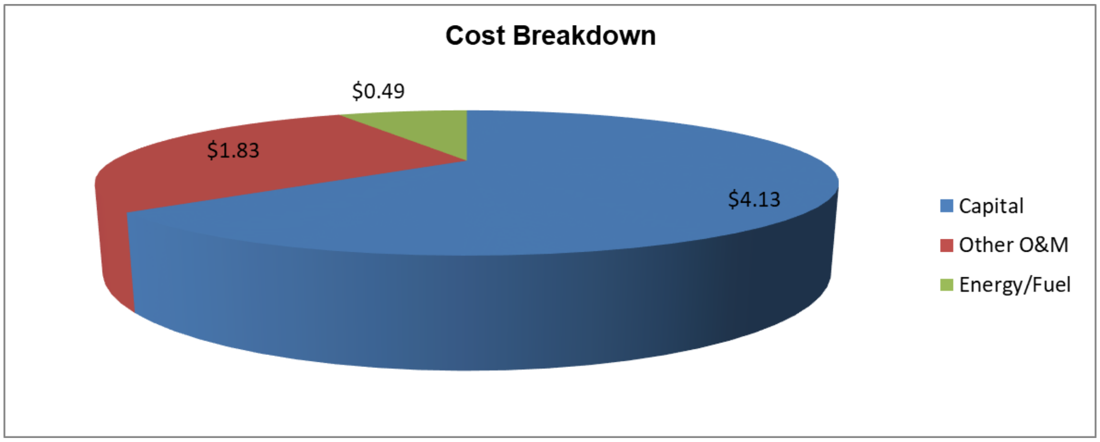


Figure 7.8. Cost breakdown of gas refueling station

Cost Breakdown					
	GH2 Terminal [$/kg]	Geologic Storage [$/kg]	Compressed H2 Truck-Tube [$/kg]	Gaseous Refueling Station [$/kg]	Sum [$/kg]
Total Cost [$/kg]	$1.8160	$0.4810	$1.6581	$2.4988	$6.4538
Capital	$0.9713	$0.2059	$1.3221	$1.6356	$4.1349
Other O&M	$0.6363	$0.2743	$0.2482	$0.6687	$1.8274
Energy/Fuel	$0.2084	$0.0008	$0.0878	$0.1945	$0.4914

Table 7.1 Cost breakdown of gas refueling station

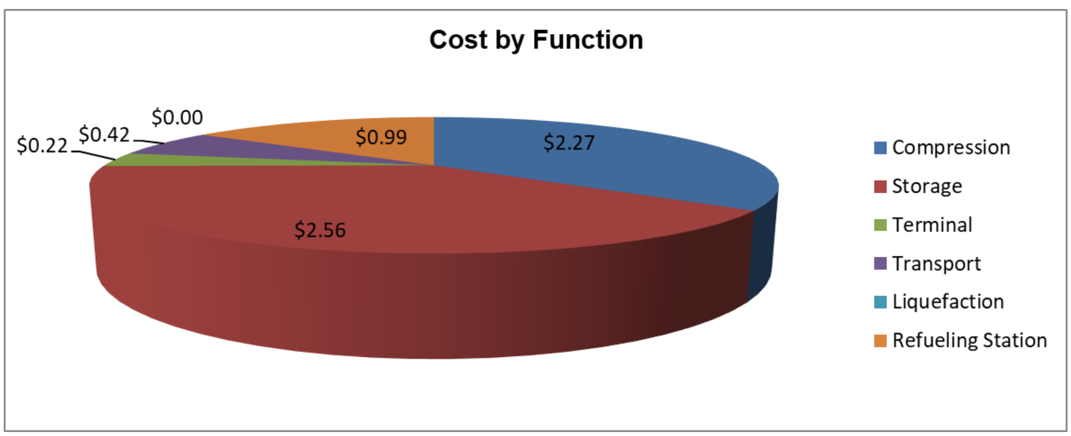


Figure 7.9 Cost by function of gas refueling station

Cost by Function $/kg						
	Compression	Storage	Terminal	Transport	Liquefaction	Refueling Station
Capital	$1.2475	$2.0643	$0.1206	$0.0942	$0.0000	$0.6083

Other O&M	$0.6918	$0.4911	$0.0994	$0.2334	$0.0000	$0.3118
Energy/Fuel	$0.3355	$0.0000	$0.0000	$0.0878	$0.0000	$0.0682
Total Cost [$/kg]	$2.2748	$2.5554	$0.2200	$0.4154	$0.0000	$0.9882

Table 7.2. Cost by function of gas refueling station

Annual Cost and Energy Breakdown, and Land Area						
	Total Capital Investment	Standard O&M (Less energy cost)	Electrical Energy Consumption (MJ)	Truck Fuel Consumption (MJ)	GH2 Terminal Land Area (m^2)	GH2 Refueling Station Land Area (m^2)
	$16,121,898	$1,037,404	9,476,624	2,574,372	5,236	997

Table 7.3. Annual Cost and Energy Breakdown, and Land Area of gas refueling station

The total unit cost by using gas hydrogen with 1000 kg/day, 700bar refueling station is about $6.45/kg. The capital cost occupies the largest fraction and can be decreased with larger market penetration.

By using liquified hydrogen with 2 refueling stations (capacity: 1600 kg/day, 700bar)

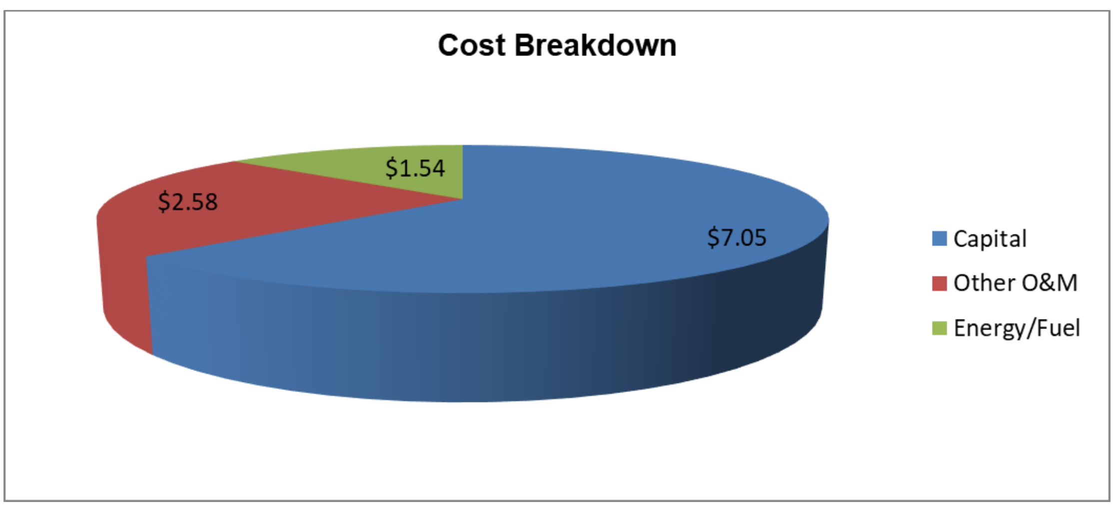


Figure 7.10. Cost breakdown of liquid refueling station

Cost Breakdown					
	Liquefier [$/kg]	Terminal [$/kg]	Tractor-Trailer [$/kg]	Liquid Refueling Station [$/kg]	Sum [$/kg]
Total Cost [$/kg]	$4.92	$2.33	$0.54	$3.39	$11.18
Capital	$2.89	$1.63	$0.45	$2.09	$7.05
Other O&M	$0.97	$0.70	$0.08	$0.83	$2.58
Energy/Fuel	$1.06	$0.00	$0.02	$0.47	$1.54

Table 7.4. Cost breakdown of liquid refueling station

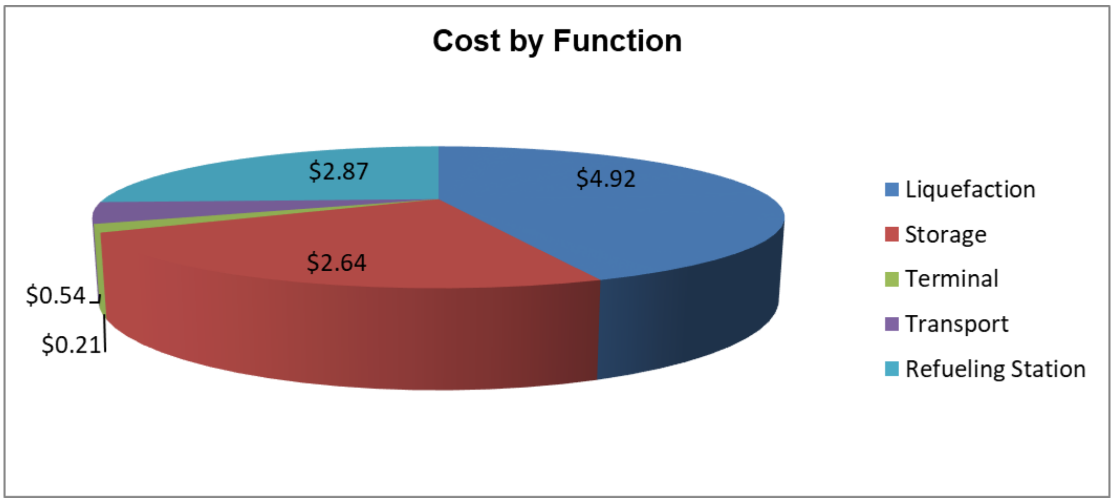


Figure 7.11. Cost by function of liquid refueling station

Cost by Function $/kg					
	Liquefaction	Storage	Terminal	Transport	Refueling Station
Capital	$2.89	$1.89	$0.14	$0.45	$1.68
Other O&M	$0.97	$0.76	$0.00	$0.08	$0.72
Energy/Fuel	$1.06	$0.00	$0.06	$0.02	$0.47
Total Cost [$/kg]	$4.92	$2.64	$0.21	$0.54	$2.87

Table 7.5. Cost by function of liquid refueling station

Annual Cost and Energy Breakdown, and Land Area						
	Total Capital Investment	Standard O&M (less energy cost)	Electrical Energy Consumption (MJ)	Truck Fuel Consumption (MJ)	LH2 Terminal Land Area (m^2)	LH2 Refueling Station Land Area (m^2)

	$29,194,62 3	$1,668,495	42,039,216	490,143	7,346	2,513

Table 7.6. Annual Cost and Energy Breakdown, and Land Area of liquid refueling station

The total unit cost by using gas hydrogen with 1600 kg/day, 700bar refueling station is about $11.8/kg. It is higher than that of gas hydrogen refueling station because of the high cost of liquification. The capital cost still occupies the largest fraction.

Gas hydrogen transportation by trucks may be a more beneficial choice in which situation more refueling stations with smaller capacity are needed.

Reference:

[1] Nicholas MA, Ogden J. Detailed analysis of urban station siting for California hydrogen highway network [Internet] Transp Res Rec J Transp Res Board 2006 Jan 1 [cited 2020 Jun 29];1983(1):121-8. Available from: http:// journals.sagepub.com/doi/10.1177/0361198106198300117.

[2] National Research Council. Transitions to alternative transportation technologies-A focus on hydrogen. In: Transitions to alternative trans- portation technologies-A focus on hydrogen. National Academies Press; 2008. p. 1-126.

[3] Lin Z, Chen C-W, Ogden J, Fan Y. The least-cost hydrogen for Southern Cal- ifornia. Int J Hydrogen Energy 2008;33(12).

[4] Nicholas MA, Handy SL, Sperling D. Using geographic information systems to evaluate siting and networks of hydrogen stations. Transp res rec J transp res board [Internet]. 2004 Jan 1 [cited 2020 Jun 23];1880(1):126-34. Available from: http://journals.sagepub.com/doi/10.3141/1880-15.

[5] Lin Z, Ogden J, Fan Y, Chen C-W. The fuel-travel-back approach to hydrogen station siting. Int J Hydrogen Energy 2008;33(12).

[6] Kim JG, Kuby M. The deviation-flow refueling location model for optimizing a network of refueling stations. Int J Hydrogen Energy 2012 Mar 1;37(6):5406-20.

[7] Zhao Q, Kelley SB, Xiao F, Kuby MJ. A multi-scale framework for fuel station location: from highways to street intersections. Transport Res Transport Environ 2019 Sep 1;74:48-64.

[8] Ogden J, Nicholas M. Analysis of a “cluster” strategy for introducing hydrogen vehicles in Southern California. Energy Pol 2011 Apr 1;39(4):1923-38.

[9] Kuby M, Lines L, Schultz R, Xie Z, Kim JG, Lim S. Optimization of hydrogen stations in Florida using the flow-refueling location model. Int J Hydrogen Energy 2009 Aug 1;34(15):6045-64.

[10] StephensRomero SD, Brown TM, Kang JE, Recker WW, Samuelsen GS. Systematic planning to optimize investments in hydrogen infrastructure deployment. Int J Hydrogen Energy 2010 May 1;35(10):4652-67.

[11] Melaina MW. Initiating hydrogen infrastructures: preliminary analysis of a sufficient number of initial hydrogen stations in the US. In: International journal of hydrogen energy. Pergamon; 2003. p. 743e55.

[12] Nicholas MA. Driving demand: what can gasoline refueling patterns tell us about planning an alternative fuel network? J Transport Geogr 2010 Nov1;18(6):738e49.

[13] Pacific Northwest National Laboratory (PNNL). H2 tools: international hydrogen fueling stations [Internet], [cited 2020 Sep 5]. Available from: https://h2tools.org/hyarc/hydrogen-data/international-hydrogen-fueling- stations; 2020.

[14] Alternative Fuels Data Center (AFDC). Hydrogen fueling stations [Internet]. [cited 2020 Sep 5]. Available from: https://afdc.energy.gov/fuels/hydrogen_ stations.html.

[15] Khan, U., Yamamoto, T., & Sato, H. (2021). Understanding attitudes of hydrogen fuel-cell vehicle adopters in Japan. International Journal of Hydrogen Energy, 46(60), 30698–30717. https://doi-org.proxy.library.cornell.edu/10.1016/j.ijhydene.2021.06.195

[16] International Energy Agency. (2019). The Future of Hydrogen: Seizing today's opportunities. OECD Publications Centre: OECD Publications Centre. Retrieved from https://resolver.ebscohost.com/Redirect/PRL?EPPackageLocationID=3949.22741035.49134173&epcustomerid=s9001366

[17] Godula-Jopek, A., Jehle, W., & Wellnitz Joŕg. (2012). Hydrogen storage technologies: new materials, transport, and infrastructure. Weinheim: Wiley-VCH. Retrieved from https://resolver.ebscohost.com/Redirect/PRL?EPPackageLocationID=2106155.1381744.21618751&epcustomerid=s9001366

[18] Khan, U., Yamamoto, T., & Sato, H. (2021). An insight into potential early adopters of hydrogen fuel-cell vehicles in Japan. International Journal of Hydrogen Energy, 46(18), 10589–10607. https://doi-org.proxy.library.cornell.edu/10.1016/j.ijhydene.2020.12.173

[19] Greene, D. L., Ogden, J. M., & Lin, Z. (2020). Challenges in the designing, planning and deployment of hydrogen refueling infrastructure for fuel cell electric vehicles. ETransportation, 6. https://doi-org.proxy.library.cornell.edu/10.1016/j.etran.2020.100086

[20] Ogden, J., & Nicholas, M. (2011). Analysis of a "cluster" strategy for introducing hydrogen vehicles in Southern California. Energy Policy, 39(4), 1923–1938. https://doi-org.proxy.library.cornell.edu/10.1016/j.enpol.2011.01.005

[21] CaFCP road map for procurement of fuel cell buses in California. (2019). Fuel Cells Bulletin, 2019(10), 10. https://doi-org.proxy.library.cornell.edu/10.1016/S1464-2859(19)30425-0

Hall, W., Spencer, T., Renjith, G., and Dayal, S. 2020. The Potential Role of Hydrogen in India: A pathway for scaling-up low carbon hydrogen across the economy. New Delhi: The Energy and Resources Institute (TERI).

Annual Reports. (2017). TCAT. Retrieved October 27, 2021, from https://tcatbus.com/about/annual-reports

MTA. (2020, April 14). Subway and bus facts 2019. https://new.mta.info/agency/new-york-city-transit/subway-bus-facts-2019

MTA. (2021, June). Capital Program Oversight Committee Meeting. https://new.mta.info/document/42401

National Renewable Energy Laboratory. (2006, November). New York City Transit (NYCT) Hybrid (125 Order) and CNG Transit Buses. https://www.nrel.gov/docs/fy07osti/40125.pdf

Mayor ‘s Office of Sustainability. (2021). INVENTORY OF NEW YORK CITY GREENHOUSE GAS EMISSIONS. Https://Nyc-Ghg-Inventory.Cusp.Nyu.Edu/. https://nyc-ghg-inventory.cusp.nyu.edu/

https://www.sciencedirect.com/science/article/pii/S0920586108004100?casa_token=Jf_4VPpfmHIAAAAA:HiTpf5Mii_QvqM30lZpYoDuk-T8ebMUOK_7r0PO4CD-oSOdZdgNFiUdrwNMn5BbbggVjfaFs

https://www.sciencedirect.com/science/article/pii/S036031990700482X?casa_token=1LH8CD1Uqb8AAAAA:w8JqI5xCH91f8MIM4jGdjYzPU-9wILJuV7R7iccKcLnzmguygHh0MG_75xgEGxHJCkNNFWxw

1. https://www.eia.gov/energyexplained/hydrogen/

2. https://www.energy.gov/eere/fuelcells/hydrogen-resources

3. https://www.nrel.gov/research/eds-hydrogen.html

4. https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming

Applications of hydrogen fuel cells:

2.6.1

https://www.adaptalift.com.au/blog/2020-03-13-advantages-of-hydrogen-forklifts

D'Allegro, J. (2019). Elon Musk says the tech is ‘mind-bogglingly stupid,’ but hydrogen cars may yet threaten Tesla. CNBC. Retrieved from https://www.cnbc.com/2019/02/21/musk-calls-hydrogen-fuel-cells-stupid-but-tech-may-threaten-tesla.html

2.6.2

1. Why the future of long-haul heavy trucking probably includes lots of hydrogen | Greenbiz. (2021, June 15).

2. https://www.gladstein.org/hydrogen-fuel-cell-trucks/

3. 19006_hydrogen_class8_long_haul_truck_targets

4. https://www.trucks.com/2019/03/29/nikola-motor-fuel-cell-lab/

2.6.3

Thomas Walker. https://www.greenbiz.com/article/why-future-long-haul-heavy-trucking-probably-includes-lots-hydrogen

(1)http://www.chfca.ca/fuel-cells-hydrogen/hydrogen-fuel-cell-applications/

(2) https://www.fchea.org/stationary

(3)https://wha-international.com/10-hydrogen-fuel-cell-applications-you-might-not-know/

Solar Harvesting:

PVWatts - NREL. (n.d.). Https://Pvwatts.Nrel.Gov/Pvwatts.Php. Retrieved November 29, 2021, from https://pvwatts.nrel.gov/pvwatts.php

Marsh, J. (2021, June 8). *Types of solar panels*. Solar News. Retrieved November 29, 2021, from https://news.energysage.com/types-of-solar-panels/

Landau, C. R. L. (2017, March 18). *Optimum Tilt of Solar Panels*. Https://Www.Solarpaneltilt.Com/#other. Retrieved November 29, 2021, from https://www.solarpaneltilt.com/#other

Cornell green consulting group. (2011). *FEASIBILITY STUDY OF RENEWABLE ENERGY SOURCES AT THE EMERSON PLANT IN ITHACA, NY*. http://www.lightlink.com/francis/EmersonFinalReportF2011.pdf.

Ong, S. (2013). *Land-use requirements for solar power plants in the ... - NREL*. national renewable energy laboratory. Retrieved November 29, 2021, from https://www.nrel.gov/docs/fy13osti/56290.pdf.

Hyder, Z. (2019, April 23). *What is a solar farm? costs, Land Needs & more*. Solar Reviews. Retrieved December 16, 2021, from https://www.solarreviews.com/blog/what-is-a-solar-farm-do-i-need-one

---

Cover Page:

Acknowledgement

Executive Summary

List of Authors and biographies

List of tables

List of figures

Table of Contents:

Introduction: (Mingzhe) review the entire introduction and remove redundant ideas

1.1. Motivation (table 1 would be named as 1.1.a , table 2 will be 1.1.b)

1.2. Project scope and objectives

1.3. Limitations and Challenges

1.4. Project timeline

Market Analysis: (Huiya) review the entire document and remove redundant ideas

2.1. Energy consumption in India, China, and the US

2.2. Energy demand as per different modes of transport

2.3. Hydrogen generation

2.4. Hydrogen transportation and storage

2.5. Hydrogen fuel cells

2.6. Applications of Hydrogen fuel cells

2.6.1. Forklifts

2.6.2. Long distance trucking

2.6.3. Stationary applications

2.7. Deployment of hydrogen refueling infrastructure

2.7.1. Challenges

2.7.2. Policy influences

MODEL

Solar Harvesting: (Mingzhe and Nidhi)

3.1. Solar energy availability in Ithaca

3.2. Solar energy calculations (with assumptions and parameters)

3.3. Estimated cost of setting up Solar panels

Wind Harvesting: (Peter)

4.1. Wind energy availability near Ithaca

4.2. Wind energy calculations

4.3. Estimated cost of setting up wind turbines.

Electrolyzers: (Yuxiang)

5.1. Choice of electrolyzer

5.2. Cost of setting-up the electrolyzer

Hydrogen storage: (Nidhi) ----> (Qizhou)

6.1. Hydrogen storage plant layout

6.2. Hydrogen storage tank

6.3. Cost estimate

Hydrogen Fuel cells: (Nidhi) ----> (Yuxiang)

7.1. Choice of Fuel cell

7.2. Cost estimate

Cost of overall hydrogen production (Peter 8.1 and 8.2 Yuxiang)

8.1. Comparison with traditional prices (add up all the above cost vs the existing prices)

8.2. Annual cost savings using hydrogen fuel cells

8.3. Model Integration--Peter

8.4 Sensitivity analysis

Applications: (Huiya and Qizhou)

9.1. Mini-buses in Chainworks

9.2. Connection to microgrid

9.3. Deployment of refueling infrastructure

Discussion, Conclusion and future work:

Critique our work

What else could we have done

talk about CHP (Huiya, Mingzhe)

Suggest improvements, areas of research, further investigation

Future prospects for hydrogen

Reduction of costs in the future (Peter)

Summary of applications, why hydrogen is important

References and Bibliography:

10.1. References and citations

10.2. Bibliography

Appendix

Reference

1.

India Energy Information | Enerdata. (2020). India Energy Information. Retrieved October 19, 2021, from https://www.enerdata.net/estore/energy-market/india/

United States Department of Energy, Office of Fossil Energy. (2020). *Hydrogen Strategy, Enabling a Low-Carbon Economy*. Washington, D.C. Retrieved from http://chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/viewer.html?pdfurl=https%3A%2F%2Fwww.energy.gov%2Fsites%2Fprod%2Ffiles%2F2020%2F07%2Ff76%2FUSDOE_FE_Hydrogen_Strategy_July2020.pdf&clen=3778026&chunk=true