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Sustainable Hydrogen for Long-Distance Trucking Project Final Report

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Abstract

With the current energy market leaning more and more towards using sustainable resources, hydrogen trucking has stepped into the public perspective with its zero-emission characteristic. Also, the transition towards a sustainable, low-emission transportation sector is a pressing global concern. Therefore, corporations and agencies have been finding a better alternative for goods transportation. This project explores the motivations and goals of green hydrogen trucking, an innovative approach to heavy-duty trucking that harnesses the power of renewable energy sources. A semester-long project was conducted by using examples of Wegmans' closed system in upstate New York. The study for Wegmans' system helps facilitate the design of our hydrogen fueling location. Other factors that were incorporated into the final location decisions are tank fueling efficiencies and possible truck routes. Preliminary findings of such will be added after the project is finished. The conclusion will also be added here as well by the end of our research progress.

Project Motivations & Goals

Green hydrogen trucking is a highly sustainable and environmentally friendly transportation solution that utilizes hydrogen produced from renewable sources, such as wind or solar power, to power heavy-duty trucks. Hence, by using green hydrogen as a fuel, a completely carbon-free transportation future could be achieved. More than its environmental benefits, the motivations and goals for green hydrogen trucking are rooted in addressing various economic, environmental, and energy security challenges as well. As of today, many electrical vehicles have already been put into use. Hydrogen vehicles will likely be the next step in this trend. Moreover, Hydrogen fuel cells are highly efficient and can provide even longer ranges for trucks compared to some other alternative fuels, reducing the need for frequent refueling. In addition, as technology advances and economies of scale are achieved, the cost of green hydrogen production is expected to decrease, making it a more competitive and cost-effective alternative to fossil fuels over time. Eventually, as many countries and regions implement stricter emissions regulations and

zero-emission zones, green hydrogen trucking offers a way to comply with these regulations and access restricted areas. These ultimate motivations and goals for green hydrogen trucking are highly revolving around sustainability, reducing emissions, improving air quality, enhancing energy security, and promoting economic growth. We as a team are hopeful as technology and infrastructure for green hydrogen continue to develop, it is likely to play an extremely significant role in the transition to a more sustainable and environmentally responsible transportation sector.

Project Description

Our team has approached the hydrogen trucking future with various perspectives including market analysis, route modeling, energy source analysis, environmental analysis, economic analysis, safety concerns and development, and policy and regulation review. We conducted a comprehensive market analysis of various renewable energy vehicles including electrical and hydrogen cars. Using the current market situation as an example helps us to gain a better understanding of the future of the hydrogen trucking industry. In the market analysis, we have seen a great potential for renewable energy cars' usage in many populated countries such as China and Korea since there are more readily used refueling stations among their cities with a large percentage of the population using such vehicles. However, the situation for hydrogen vehicles could be drastically different in America. With the results of the modeling and energy sources, the final project will be able to predict the future hydrogen trucking infrastructure realistically. Our expected outcome will be increased adoption of green hydrogen technology in the heavy-duty trucking industry, leading to a reduction in carbon emissions and improved air quality by conducting a feasible refueling station system in the United States. The Green Hydrogen Trucking project aims to drive the transformation of the heavy-duty trucking industry toward sustainability, offering a scalable and environmentally responsible solution to the pressing challenges of emissions and air quality in transportation.

Team Introduction

Zhuoyao Song

Zhuoyao Song is currently a Master of Engineering Student in the School of Civil and Environmental Engineering at Cornell University. His focus is on transportation system engineering. He also holds a Bachelor of Science Degree in Civil Engineering from Rensselaer Polytechnic Institute, Troy, NY. Zhuoyao gained previous full time work experience from HBK Engineering, and internship experience from Volvo Construction Equipment and Tongji Architectural Design Group.

Claire Li

Claire Li is currently a Master of Engineering Student majoring in Environmental Engineering at Cornell University. Her academic focus is renewable energy. She holds a Bachelor degree in Environmental Studies and Mathematics from the University of Waterloo, Ontario, Canada. Claire has one year of work experience at Guidehouse as an Energy Consultant, and several internship experience as a consultant and a environmental coordinator in the green building consulting and the construction industry.

Jacky Cheng

Zhijie Cheng, a graduate from Cornell University's College of Engineering, has earned a Bachelor of Science in Civil Engineering with a concentration in Transportation and is on track to obtain a Master's in the same discipline by May 2024. Zhijie's expertise spans from sustainable transportation design to renewable energy systems, bolstered by a rich arsenal of technical skills, including proficiency in MATLAB, Python, and AutoCAD. His professional journey has taken him from SCG America in New York to Shanghai, where he contributed to urban development and architectural design. A dedicated leader, Zhijie has also demonstrated excellence in academia as a Graduate Teaching Specialist and contributed to community engagement as the Treasurer for the Chinese Dragon Soccer Club.

Cheyenne Zhang

Cheyenne Zhang is a Master of Engineering student in the School of Civil and Environmental Engineering at Cornell University. She is interested in applications of optimization and statistical learning in transportation systems. Cheyenne holds a BS in civil engineering and a BA in political science from the University of Washington, Seattle. She has also worked as a transportation engineer in the Washington Department of Transportation in Seattle, WA.

Modeling

Overview

Wegmans Food Markets has implemented an innovative approach to enhance its distribution operations and environmental sustainability by incorporating hydrogen fuel cell technology into its fleet of material-handling equipment. This pioneering move, first executed at their Pottsville, Pennsylvania warehouse, marks a significant step towards greener logistics practices. Wegmans has deployed a fleet of 50 hydrogen fuel cell-powered pallet trucks to facilitate the movement of produce destined for its stores across five states.

This initiative not only boosts productivity by maintaining consistent performance regardless of fuel levels, as highlighted by Wegmans' Retail Service Center maintenance manager, but it also aligns with their ongoing commitment to sustainability. The utilization of hydrogen fuel cells, which emit only heat and water as byproducts, offers a clean energy alternative, reducing the carbon footprint traditionally associated with such operations.

For this project, we aim to design a closed system for hydrogen trucking for Wegmans in upstate New York. This system will involve using hydrogen fuel cell-powered trucks for the efficient and eco-friendly transport of goods. While we do not have an official collaboration with Wegmans, our model draws from publicly available data, including Wegmans' website. This model offers a practical example of integrating green hydrogen technology into commercial trucking operations, further optimizing the most challenging aspects of logistics and distribution through advanced linear programming to determine the most efficient vehicle routes.

Model Goals

- **Minimization of Distance:** The primary goal of the model is to minimize the total distance traveled by the fleet, thereby reducing fuel consumption and travel time.
- **Balanced Workload:** It ensures that the visit count for each location meets a specified minimum requirement, promoting balanced service delivery across all points.
- **Maximization of Efficiency:** By setting a maximum allowable distance per vehicle, it ensures that each vehicle is used optimally without exceeding operational constraints.

Key Assumption

Refueling Station at Distribution Center: Placing the refueling station at the distribution center is a strategic decision that brings multiple benefits to the model's design, particularly for Wegmans' hydrogen trucking system. Centralizing fueling operations at the hub of distribution activities allows for efficient use of resources and time. Trucks can commence their routes with a full tank of hydrogen and return for immediate refueling, eliminating the need for additional fueling infrastructure or unnecessary deviations from their routes.

Given that the maximum distance covered by the trucks is around 500 miles, most round-trip journeys from the distribution center are well within this range, ensuring that the vehicles can operate without the risk of running out of fuel. This not only reduces "range anxiety" but also increases vehicle uptime, as the rapid refueling capability of hydrogen fuel cells significantly cuts down the idle time compared to the longer charging periods required for battery-powered trucks.

Moreover, this setup contributes to operational cost savings by leveraging economies of scale for the fuel, and it enhances sustainability by supporting the continuous use of green technology. As Wegmans looks to expand its fleet or extend operational ranges, the scalability of having an on-site refueling station ensures that the company can maintain these efficiencies. Additionally, housing the refueling infrastructure within the distribution center streamlines safety protocols and regulatory compliance, further cementing the model's viability and alignment with the company's commitment to innovative, sustainable logistics solutions.

Other Assumptions

- Distance Metrics: The model assumes that the distances between locations are known and consistent.
- Homogeneous Fleet: All vehicles in the fleet are assumed to have the same capacity and travel distance capabilities.
- Static Conditions: It assumes that traffic conditions, vehicle speeds, and other dynamic factors remain constant, which may not reflect real-world variability.
- Binary Routing: Decisions are binary; a vehicle either travels from point A to B or it does not, there's no partial servicing.
- Closed Routes: Each vehicle route starts and ends at the distribution center, forming a closed loop.
- No Time Windows: Delivery or service time constraints at locations are not considered, focusing purely on distance optimization.

Application Scenarios

This model is ideal for organizations that manage delivery services, courier companies, public transportation networks, or any operation that requires frequent visits to multiple locations and seeks to do so with high efficiency and reduced operational costs.

Benefits

- Cost Savings: By minimizing travel distances, companies can significantly cut down on fuel expenses and vehicle wear-and-tear.
- Environmental Impact: Reduced travel distances also mean a lower carbon footprint, contributing to environmental sustainability efforts.
- Scalability: This model can be scaled to accommodate different fleet sizes and complex route planning scenarios.
- Adaptability: With minor modifications, the model can adapt to various constraints and objectives, such as time windows, vehicle capacities, or prioritized deliveries.

Demo

```
# Distance matrix example
distance_matrix = [
    [0, 76, 88, 90, 102], # Rochester to Rochester, Buffalo, Syracuse, Ithaca, Corning
    [76, 0, 149, 153, 124], # Buffalo to Rochester, Buffalo, Syracuse, Ithaca, Corning
    [88, 149, 0, 54, 98], # Syracuse to Rochester, Buffalo, Syracuse, Ithaca, Corning
    [90, 153, 54, 0, 42], # Ithaca to Rochester, Buffalo, Syracuse, Ithaca, Corning
    [102, 124, 98, 42, 0] # Corning to Rochester, Buffalo, Syracuse, Ithaca, Corning
]

# Number of vehicles
num_vehicles = 5

# Each node needs to be visited at least this count
visit_count = 2

# Maximum distance for each vehicle
max_distance_per_vehicle = 380
```

Figure 1. Parameters of the Model

```
Objective value: 876.00000000
Enumerated nodes: 166
Total iterations: 8108
Time (CPU seconds): 0.40
Time (Wallclock seconds): 0.41

Option for printingOptions changed from normal to all
Total time (CPU seconds): 0.40 (Wallclock seconds): 0.41

Route for vehicle 0: 0 -> 2 -> 3 -> 4 -> 0
Route for vehicle 1: 0
Route for vehicle 2: 0 -> 1 -> 0
Route for vehicle 3: 0 -> 1 -> 0
Route for vehicle 4: 0 -> 2 -> 3 -> 4 -> 0
```

Figure 2. Result of the Model

The model, as detailed in Figure 1, has been meticulously configured with parameters that are integral to its operational efficiency. The `distance\_matrix` is the cornerstone, establishing the exact distances between specific locations such as Rochester, Buffalo, Syracuse, Ithaca, and Corning. With `num\_vehicles` set to 5, the fleet is adequately sized to manage the routes effectively.

The `'visit_count'` parameter ensures a robust level of service by mandating that each location is visited at least twice, ensuring consistency in deliveries or services provided. The `'max_distance_per_vehicle'` constraint caps individual vehicle routes at 380 miles, a strategic decision that optimizes route planning while preventing any single vehicle from being overextended.

The results, as shown in Figure 2, confirm the model's high performance, achieving an optimal `'objective value'` of 876. This figure represents the total minimized distance that the fleet covers to service all routes. The computational efficiency is evident, with the model arriving at a solution in less than half a second of both CPU and Wallclock time, despite navigating through numerous iterations and nodes.

The delineated routes for each vehicle illustrate a strategic allocation of nodes, excluding vehicle 1 which is out of service. Vehicle 0, for instance, embarks on a comprehensive journey from the depot, traveling through a sequence of nodes, and eventually returning to the starting point. This planned sequence ensures that the distance and visit constraints are fully adhered to. It's important to note that within these vehicles, vehicle 1 is non-operational, which implies that only 4 trucks are necessary in this case.

It is essential to recognize that the parameters used here are a simplified abstraction of a more complex reality. In practice, there are approximately 50 stores in upstate New York, and each store requires about 10 visits daily. For the purposes of calculation efficiency and model clarity, these figures have been streamlined. This simplification allows for a more rapid computation while still providing valuable insights into the practical application of green hydrogen technology in commercial trucking operations. The model stands as a testament to the possibilities of optimizing vehicle routes in a realistic logistical framework, balancing operational demands with environmental considerations.

Energy Source Analysis

In this section, we aim to carry out literature reviews and research on the sources, production, storage, and market potential of various types of hydrogen that can be considered to power hydrogen fuel cell trucks.

The spectrum of Hydrogen

Based on the discussion with current practitioners and initial research, we came across a spectrum of colored hydrogen including green, blue, grey, turquoise, brown, pink, and white hydrogen (Kusoglu, 2022) (Incer-Valverde et al., 2023). Below we provide a brief introduction and definition of each color of hydrogen source with a greater focus on the characteristics of green and blue hydrogen, which we think would be most feasible and economically competitive for powering hydrogen fuel cell trucks.

Green Hydrogen

Green hydrogen is produced using renewable energy sources, typically through the process of electrolysis, where water is split into hydrogen and oxygen using electricity generated from renewable sources like wind or solar power (Incer-Valverde et al., 2023). Green hydrogen produced from solar-generated electricity is considered to be a carbon-neutral and most environmentally friendly method with a minimal carbon footprint, making it the best-fitted sustainable and clean energy source for hydrogen fuel cell trucking.

Blue Hydrogen

Blue hydrogen is produced from natural gas through the process of steam reforming, which combines natural gas and heated water in the form of steam to generate hydrogen (Incer-Valverde et al., 2023). However, this process still generates CO₂, and the carbon emissions are captured and stored using carbon capture and storage (CCS) technologies with around 85 ~ 95% capture rate (Kusoglu, 2022). While not entirely carbon-neutral, blue hydrogen is considered a cleaner alternative to traditional grey hydrogen, as the carbon emissions are significantly reduced through the application of CCS.

Grey Hydrogen

Grey hydrogen is the most common type and is produced through the process of steam methane reforming (SMR), which involves extracting hydrogen from natural gas similar to blue hydrogen production (Kusoglu, 2022). However, this process releases carbon dioxide as a by-product without any capturing measures in place. Grey hydrogen is considered less environmentally friendly compared to green and blue hydrogen because of its direct contribution to carbon emissions.

Turquoise Hydrogen

Turquoise hydrogen is a relatively new concept that involves the pyrolysis of methane, a process that doesn't produce carbon dioxide as a by-product (Kusoglu, 2022). This method is still in the early stages of development, but if successfully scaled, turquoise hydrogen could provide a low-carbon or carbon-free alternative to traditional hydrogen production methods.

Brown Hydrogen

Brown hydrogen is produced from natural gas through processes like coal gasification or partial oxidation, but with higher carbon emissions (Kusoglu, 2022). This form of hydrogen production is considered less environmentally friendly, and efforts are being made to transition away from brown hydrogen in favor of cleaner alternatives, so it is not an option to consider for this study.

Pink Hydrogen

Pink hydrogen is produced from electrolysis specifically powered by nuclear energy. It is also a carbon-free hydrogen source, but it is not commercially available in New York State up to the date of research (Kusoglu, 2022). Pink hydrogen is in the early stages of development, but if successful, it could offer a novel and cleaner approach to hydrogen production.

White Hydrogen

White hydrogen refers to naturally occurring hydrogens that usually sit in Earth's crust. While efforts are being invested to discover and harvest white hydrogen deposits, it is yet close to the point of large-scale production and commercialization (Kusoglu, 2022).

Facility Requirements for Green Hydrogen Refueling Station

Based on the hydrogen source research, we determine that adopting 100% green hydrogen for our trucking system is the most beneficial and practical option. Although blue hydrogen is a good supplemental option for partial demand, we have not located any existing blue hydrogen generation facility in the study area, and the cost to install and operate two systems in parallel (blue and green hydrogen production) is too high for a closed system of the defined scale. Therefore, we will move on with solely green hydrogen supply in refueling stations for this study.

Here we investigate the facility requirements to bring green hydrogen to refueling stations for long-haul trucks in our closed system. Setting up a green hydrogen refueling station involves several key facilities and components to ensure the safe and efficient production, storage, and dispensing of hydrogen. Figure 3 provides an idea of how green hydrogen is integrated as a fueling gas.

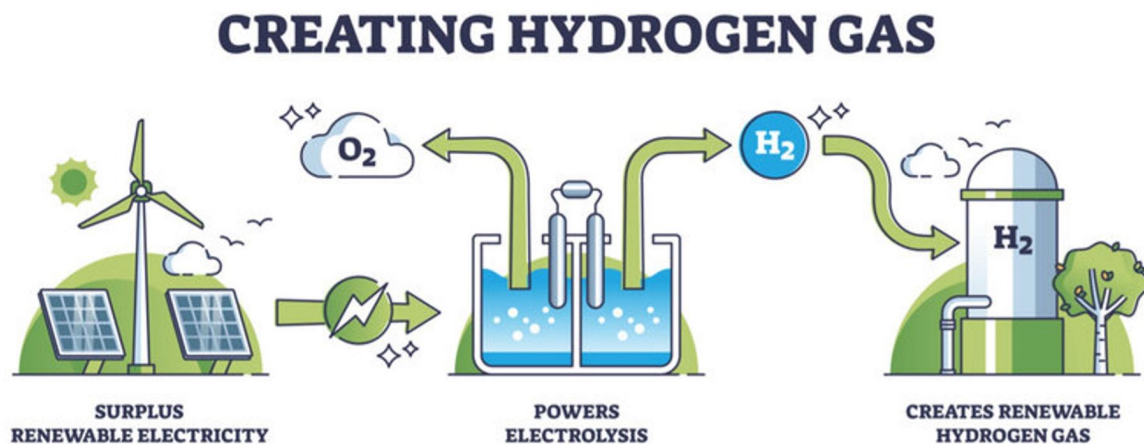


Figure 3. Electrolysis Hydrogen (Retrieved from: https://stock.adobe.com/search/images?k=electrolysis+hydrogen&asset_id=566266818)

We are adopting the onsite production and refueling design, where solar panels or small-scale onshore wind farms are directly installed onsite to generate electricity, which then powers the

electrolyzers for green hydrogen production (Rose & Neumann, 2020). Green hydrogen is then compressed into liquid or high-density gas and stored in tanks that connect to the dispensers, or directly in bars for refueling (Rose & Neumann, 2020). The average storage is around 120 kg/day per tank and the estimated total construction and commissioned cost of \$3.2 million. Per such unit combination (See figure 4). Capacity can be expanded with additional solar panels and electrolyzers based on the volume of demand, but benefit-cost analysis should be in place for planning.

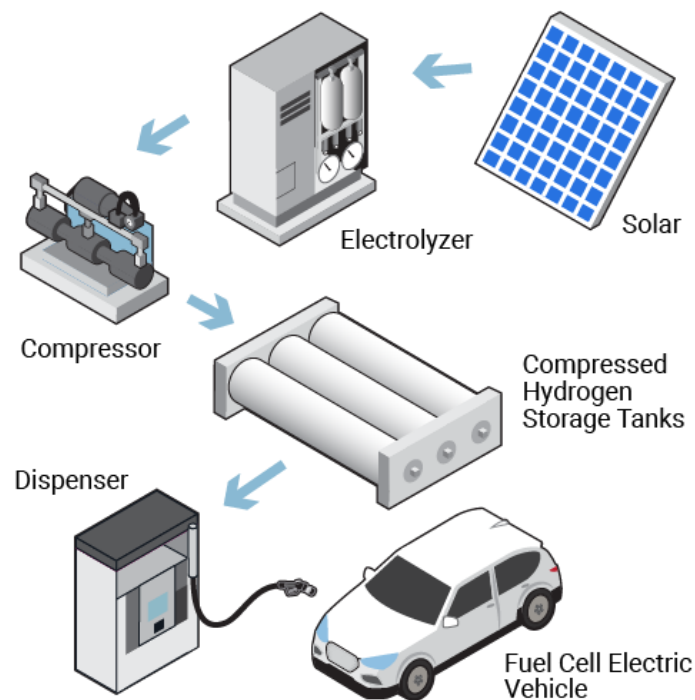


Figure 4. On-site Hydrogen Production and Refueling Stations (Retrieved from: <https://h2stationmaps.com/costs-and-financing>)

In the process of operation and production, several essential facilities are needed for a green hydrogen refueling station.

1. Electrolyzer

A green hydrogen refueling station begins with an electrolyzer, which is the device that uses electricity to split water (H_2O) into hydrogen (H_2) and oxygen (O_2) (Kumar & Lim, 2022). This process is typically powered by renewable energy sources such as solar or wind (Kumar & Lim, 2022).

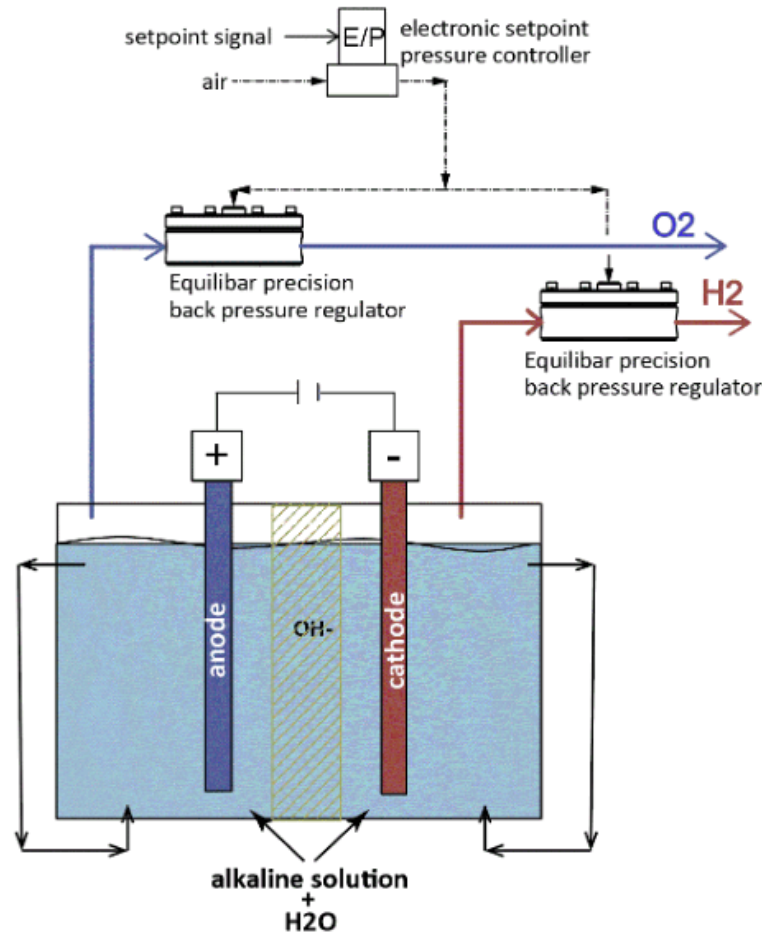


Figure 5. Alkaline electrolysis system using Equilibar BPR for H₂ and O₂ pressure control (Equilibar, 2022).

2. Clean (Solar) Electricity Source

To produce green hydrogen, the refueling station needs a reliable and renewable source of electricity, such as solar panels or wind turbines (Kumar & Lim, 2022). This energy source powers the electrolyzer, ensuring that the hydrogen production process is environmentally friendly.

3. Water Supply and Treatment

A steady supply of clean water is essential for the electrolysis process. Water treatment facilities may be required to ensure the water used is of high quality and does not contain impurities that could affect the electrolyzer's performance (Rose & Neumann, 2020).

4. Hydrogen Compression System

Once produced, hydrogen needs to be compressed for efficient storage and transportation. A compression system raises the pressure of the hydrogen to the levels required for refueling vehicles (Kumar & Lim, 2022) (Rose & Neumann, 2020).

5. Hydrogen Storage

Hydrogen is stored on-site in tanks or other storage systems. Storage options include gaseous and liquid hydrogen storage, with the choice depending on factors like space constraints and station requirements (Rose & Neumann, 2020).

Based on the nature of our designed system, hydrogen is mainly used as a given energy source for long-haul trucks owned by the grocery company, which is not responsible for the generation and production of green hydrogen onsite (Rose & Neumann, 2020). As of today, some energy providers such as ExxonMobil and Bloom Energy have shown interest in hydrogen production developments as a fueling option for commercial vehicles, and Bloom Energy plans to adopt Electrolysers and focus on green hydrogen production (ExxonMobil, 2022). Such prospect in green hydrogen production favors our blueprint for the system that green hydrogen can be transported and used commercially as an alternative fuel for long-haul trucking in New York State.

Green Hydrogen Capacity, Price, and Energy Efficiency

As of 2022, there are 33 operational green hydrogen facilities planned or proposed across the North American region with a current capacity of 691 thousand tonnes per annum (MTPA) (Panchenko et al., 2023). However, there are no individual production plants currently in operation to produce commercially available green hydrogen. In the United States, there are 5 green hydrogen projects planned for 2023 which are already in the construction stage and are

expected to start operation by 2024 (Airswift, 2023). Below is a list of these 5 projects that we believe can contribute to refueling station planning of our designed system (Airswift, 2023):

Table 1. Capacity and Coverage of Green Hydrogen Plants

Project	Capacity	Region of Coverage	Owner
St. Gabriel Green Hydrogen Plant	15 tonnes/day in 2023, 500 tonnes/day by 2025, 1000 tonnes/day by 2028.	Joins Plug's growing national network of hydrogen plants in different regions, such as New York, Tennessee, Georgia, Texas and California.	Plug Power Inc and Olin Corporation joint venture - Hidrogenii
Sauk Valley Green Hydrogen Plant	52 tonnes/year at a rate of 6 kg/hour, plus 400 kg liquid storage on site.	Illinois	Invenergy
Kingsland Green Hydrogen Plant	15 tonnes/day	Georgia	Plug Power Inc
Casa Grande Green Hydrogen Plant	10 tonnes/day	Arizona	Air Products
Donaldsonville Green Hydrogen Project	20 MW	Louisiana	CF Industries, ThyssenKrupp

According to IRENA, green hydrogen now costs around USD 4-6/kg on average and is predicted to drop to around USD 1.5/kg by 2050 (IRENA, 2021). The energy efficiency of hydrogen by electrolysis commonly recognized right now is 33 kWh/kg (Panchenko et al., 2023).

Since the main motivation for most stakeholders and practitioners to adopt hydrogen trucks is to reduce carbon emissions and reach the net-zero goal, we cannot overlook the role of emissions in this analysis. In this study, we are adopting 100% green hydrogen fuel and assuming zero carbon emission from the operation of the closed system. We are calculating emission reduction based on a comparison to the emission released from the combustion of conventional fuel with the same number of truck miles in operation.

Economic Analysis

In this section, the vehicle selection criteria are outlined, followed by a detailed breakdown of the vehicle costs, and the fuel cost analysis (we are in an early stage of the hydrogen trucking industry so the result might not be accurate when things come out in the future, just take it as a reference), the infrastructure costs which mainly is the refueling stations cost. In addition, the economic benefits are discussed including potential economic benefits of transitioning to hydrogen, such as job creation in the hydrogen industry.

Vehicle Selection

The Number of Trucks needed for Wegmans in NY state is calculated based on the ratio of their stores in NY State. As of July 2023, Wegmans has 109 stores total in operation, and 48 are in NY state. Wegmans owns 175 trucks in total. So the number of trucks needed in NY state can be calculated (assumed in an easier way):

$$\text{Number of Trucks needed} = 175 \times \frac{48}{109} = 77 \text{ trucks}$$

When we are looking for the models we want to use, there are two big companies that are working on hydrogen trucks in the US, one is called HYZON, and the other is NIKOLA. Both truck models are shown in Figure 6.0 and Figure 6.1. We compare some key specifications below in Table 2.0

	Range	Fuel Capacity	Horsepower	Refueling time	Cost
HYZON	350 mile	50 kg	374 hp	15 min	\$400,000 ~ \$500,000
NIKOLA	500 mile	70 kg	576hp	< 20 min	\$450,000

Table 2.0 HYZON and NIKOLA Model Comparison

After looking into both of them, we picked NIKOLA's Tre FCEV model since it has more horsepower and longer range of 500 miles compared to the 350 miles range HYZON provides while at the same price level. Nikola's model can store 70 kg of hydrogen gas and has a little more refueling time compared to HYZON. It is not a big problem since having a refueling time of less than 20 minutes is already acceptable compared to hours of recharging time from electric vehicles.



Figure 6.0 HYZON HYHD 8-200 Model

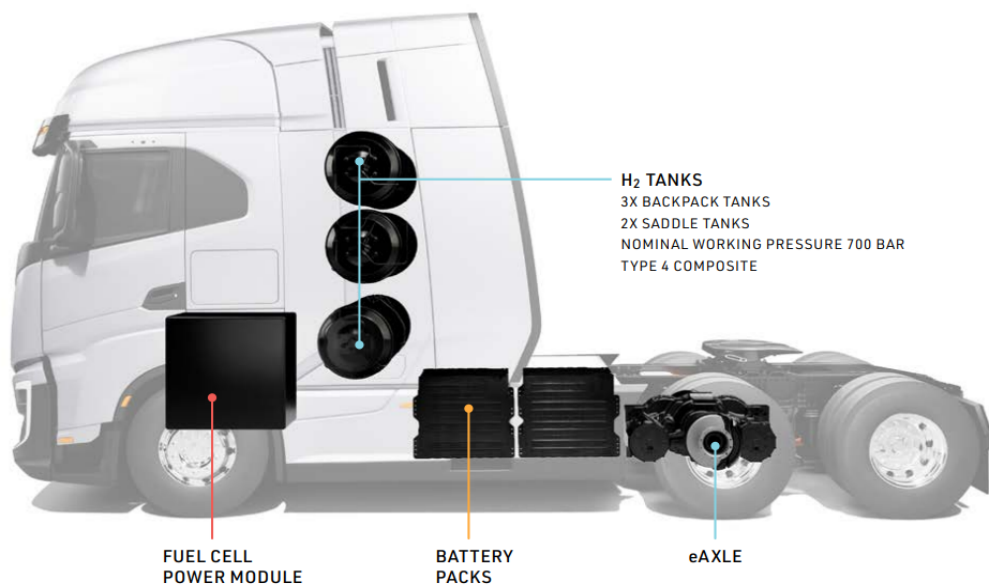


Figure 6.1 NIKOLA TRE FCEV Model

Besides that, Nikola company surpassed 200 orders for hydrogen fuel cell trucks in August 2023 (Alan, 2023). Above is an image of the TRE FCEV model (see Figure 6.1) from their official website showing the truck itself.

Some key parameters of the TRE FCEV model again: It has a max range of 500 miles, a refuel time of 20 minutes at most, 536 continuous horsepower, and 82,000 lb in weight.

As we can see in Figure 6.1 the cylinders are where the truck stores the hydrogen and they also have the batteries down at the bottom, and just want to clarify that these trucks run on electricity produced in the hydrogen-powered fuel cell and it mixes hydrogen and oxygen to produce electricity. Some of that electricity is used immediately and some is stored in those batteries.

Vehicle Cost

The unit price for this model is \$450,000 (EV Pulse, 2023). The New York State Energy Research and Development Authority also provides incentives for this kind of Hydrogen Fuel Cell Electric Trucks, they will offer a \$185,000 incentive (Table 2.1) for class 4-8 All-Electric and Hydrogen Fuel Cell Electric Trucks. So that makes the truck more affordable for purchasing. So although it is still a little more expensive after the incentives compared to the diesel trucks (which are priced around \$140,000 to \$200,000), they will have less maintenance cost which we will introduce later in the report.

Technology Type	Incentive Amount
Class 4-8 All-Electric and Hydrogen Fuel Cell Electric Trucks	95% of the incremental cost, up to \$185,000 per vehicle
Class 4-8 All-Electric and Hydrogen Fuel Cell Electric Transit Buses	100% of the incremental cost, up to \$385,000 per vehicle
Class 4-8 Paratransit Shuttle Buses	100% of the incremental cost, up to \$150,000 per vehicle
Class 4-8 All-Electric School Buses	100% of the incremental cost, up to \$220,000 per vehicle
All-Electric Non-Road Port Cargo Handling Equipment	90% of the incremental cost, up to \$170,000 per vehicle
Repower All-Electric Non-Road Port Cargo Handling Equipment	90% of the incremental cost, up to \$140,000

Table 2.1 New York Truck Voucher Incentive Program

In summary for New York State, there is a maximum of \$185,000 grant amount according to the New York Truck Voucher Incentive Program (NYTVIP) for Class 4-8 All electric and hydrogen fuel cell electric trucks. So the estimated cost for each FCEV model would be around:

$$\$450,000 - \$185,000 = \$265,000$$

Therefore, the total amount needed for New York State is the unit price times 77 trucks needed, which is $\$265,000 \times 77 = \$10,405,000$. However, we might not need all 77 trucks to be replaced to be hydrogen fuel cell trucks, it depends on the budget Wegmans have and their plan. In addition to that, if the purchase is more than a few trucks, there will be other discounts as well. Therefore, the final price will be even lower.

Fuel Costs

There are currently 59 hydrogen refueling stations nationwide. The US department of energy has a website (https://afdc.energy.gov/fuels/hydrogen_locations.html#/find/nearest?fuel=HY) that shows all the hydrogen refueling stations as we can see in Figure 7.



Figure 7. Hydrogen Refueling Station Locations

The current hydrogen refueling stations are mostly located in Hawaii and California (in blue circles). For the eastern side, only Quebec and Toronto have hydrogen refueling stations. That's why in our case we decided Wegmans should have its own hydrogen refueling stations since there are no public stations available on the eastern coast. And that decision also refers to our project goal of building such a close system.

Therefore, we will use California as a reference since they already have a lot of the stations built and planning to build. There are 41 stations right now, and 34 are owned by a company named True Zero. When we looked into their price, hydrogen was only \$13 per kilogram in 2021, and only 2 years later, it is now \$36 per kilogram (Collins, 2023) (Figure 7.1).



Figure 7.1 True Zero Hydrogen Price

Figure 1.3 was taken by a Toyota Mirai driver, and it almost took him \$200 to fill up the tank. For True Zero's hydrogen source, only a third of their hydrogen supply is green, and the other two-thirds is made from unabated fossil gas (Collins, 2023). Therefore, their hydrogen price is

related to the price of natural gas. Also, they only served light-duty passenger cars and not heavy-duty trucks so such a high price was not reasonable for us to use. Since we are at such an early stage, we did not find any useful information or current public heavy-duty hydrogen truck refueling station, but we do know that the hydrogen refueling stations for passenger cars in Canada right now is kept at \$10 per kilogram level, and for heavy-duty truck industry we would estimate that the price of hydrogen should be under \$10 per kilogram and even around \$5 per kilogram since the truck fuel tank is up to 70kg, we have to make it affordable. However, we can't provide a more specific number right now.

Infrastructure Costs

Since California has a lot of hydrogen stations built, and they are now planning to build 111 new hydrogen stations (California Energy Commission, 2020), we will have the numbers from them as a reference as well this time. We plan to build with onsite production methods as introduced earlier in the energy sourcing section. We are going to build Solar Power Plants near the hydrogen refueling station to produce pure green hydrogen so that the price of hydrogen will not be affected by other natural resources like natural gas. According to a DOE Hydrogen Program Record in California, the cost of building a light-duty hydrogen station is \$1.9 million, while we expect a lot higher for building a heavy truck hydrogen refueling station. There is a brand under NIKOLA called HYLA, this July, the California Transportation Commission awarded them a \$41.9 million grant under the Trade Corridor Enhancement Program to build 6 heavy-duty hydrogen refueling stations across Southern California (Jeniffer, 2023). So we can expect that for each hydrogen refueling station, we will receive around \$7 million of investment, and according to HYLA, it will cost \$15 to \$20 million to build one hydrogen refueling station depending on the storage capacity (Alan, 2023).

Other Economic Benefits

Transitioning to hydrogen fuel cell trucks can bring economic benefits that go beyond just the transportation part. One of the biggest benefits is the creation of new jobs, especially in the hydrogen industry. When the demand for hydrogen fuel increases, we will need more people to

work in producing, transporting, and selling the hydrogen. This could lead to a significant increase in the number of new jobs.

In the trucking and logistics industries, using hydrogen trucks may lead to cost savings over time. These hydrogen trucks have fewer moving parts than traditional diesel trucks, which means they would need less maintenance and have a longer lifespan. This could save money for companies in the long run. However since the initial cost of the trucks looks a lot higher right now, it will eventually come down when the technology is mature and widely used.

In addition, as the hydrogen industry grows, it could lead to some other achievements in technology and more efficient production methods. This would not only make hydrogen cheaper and more competitive with other fuels, but also it could have positive effects on industries that use similar technologies.

Environmental Analysis

The Environmental Impact Assessment for the Hydrogen Trucking Project is a crucial component in ensuring the sustainability and environmental responsibility of this innovative transportation solution. In this section, the environmental effect of using hydrogen trucking as well as the impact of building refueling stations will be discussed. By using literal references and calculations, the total environmental impact can be roughly calculated and therefore counted into the considerations of the pros and cons of using hydrogen trucking overall.

First, we will compare the emissions from conventional diesel trucks using calculations to those from renewable energy sources. Heavy-duty on-road trucks account for 70% of all freight transport and 20% of transportation-related greenhouse gas (GHG) emissions in the United States. Quiros et al. have computed several greenhouse gases, including nitrous oxide (N₂O), carbon dioxide (CO₂), and methane (CH₄). This study examined the three common greenhouse gas emissions from seven heavy-duty trucks that ran on diesel and compressed natural gas (CNG).

Because burning requires air, the result is a greater amount of CO₂ emissions than the initial weight of diesel. During the burning process, the carbon and hydrogen atoms in gasoline separate. Hydrogen and oxygen combine to form water (H₂O), whereas carbon dioxide (CO₂) is produced when carbon and oxygen come together. Since there are sixteen oxygen atoms and twelve carbon atoms in each, a CO₂ molecule has a total atomic weight of forty-four (12 carbon and 32 oxygen). To calculate the amount of CO₂ produced from a gallon of gasoline, multiply the weight of the carbon in the fuel by 44/12, or 3.7. Gasoline weighs around 87% carbon and 13% hydrogen, therefore a gallon of gasoline contains 5.5 pounds of carbon.

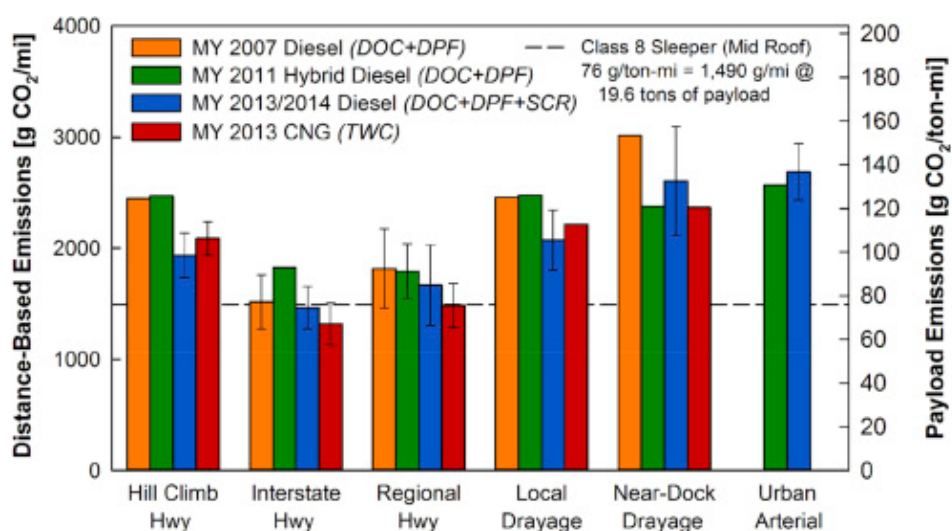


Figure 8. The CO₂ Emission Rate in Various Roads

This graphic displays the average mileage and CO₂ emissions associated with the payload for every vehicle class and route. Here, we can see that there is an average travel time of 94 ± 35 minutes. The error bars display the average trip emissions, plus or minus one standard deviation. There are two or fewer trips per route-vehicle combination when error bars are missing. The chart above represents a total of 96 trips and 148 hours of on-road data across all seven automobiles.

Although all the bars are comparatively different, there is no statistically significant difference in the CO₂ emissions from the MY 2013/2014 diesel, MY 2007 diesel, and MY 2013 CNG cars. From the article, the emission number from each of them is 1465 ± 189 g/mi, 1524 ± 239 g/mi, and 1317 ± 190 g/mi. In this calculation, the roads are also observed without extensive grades on

the Interstate Highway Route. However, some other considerations need to be included in this study despite using carbon emission rates when these trucks enter the market such as engine size.

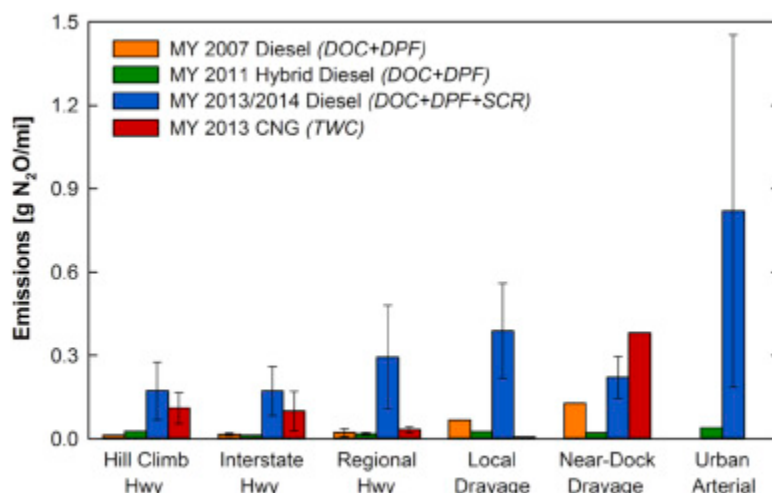


Figure 8.1. The CO2 Emission Rate in Various Roads

This chart above shows the NO₂ emissions for the trucks. All other notations are the same in the chart above. The error bars here show that the emissions from an average journey, plus or minus one standard deviation. There are less than three trips for each route-vehicle combination when error bars are not included.

Finally, the typical raw exhaust concentrations of CH₄ from diesel engines were often determined to be less than 1 part per million in this investigation. However, it should be emphasized that these estimations do not take into consideration the evaluation of any upstream CH₄ emissions from refueling, onboard emissions, or leaks in the distribution system. These emissions should be included when evaluating non-tailpipe GHG emissions from alternative fuel cars since they may represent a sizable and noticeable component.

In the meantime, the other research presents novel insights into the environmental consequences of hydrogen car use. Fuel cell buses (FCBs) and battery electric buses (BEBs) are the main topics of this study. It emphasized that in addition to already emitting zero emissions, they can reduce noise levels by up to 60%. This graph illustrates how different hydrogen sources affect total CO₂ emissions. When paired with gray hydrogen, the CO₂ emissions from FCBs are

substantially higher than those from conventional diesel buses. However, powering FCBs with green hydrogen can result in a significant drop in emissions.

Fuel type	CO₂ emission factor (f_{CO2})
Diesel	3.13 kgCO ₂ eq./l _{diesel}
'Grey' H ₂	13.20 kgCO ₂ eq./kgH ₂
'Green' H ₂	0.7 kgCO ₂ eq./kgH ₂
Electricity EU-28	0.2958 kgCO ₂ eq./kWh _{el.}
Electricity Austria	0.0851 kgCO ₂ eq./kWh _{el.}
Electricity Germany	0.4408 kgCO ₂ eq./kWh _{el.}

Figure 8.2. Fuel Type and CO₂ Emission Factor

Bus type	Savings in GHG emissions compared to diesel ICEB during the operation
FCB with 'green' H ₂	93%
BEB with electricity from EU-28	59%
BEB with electricity from Austria	88%
BEB with electricity from Germany	39%

Figure 8.3. Bus type and Savings in GHG emissions

Nonetheless, we must approach the subject of "green" hydrogen from this angle. Many people consider BEBs and FCBs to be environmentally safe technologies. The main energy sources that are used to generate electricity and hydrogen have a big impact on the environment. The environmental benefits of these alternative buses may only be realized in conjunction with

energy carriers derived from renewable or low-carbon sources. As a result, it is only sensible to use FCBs in conjunction with the generation of hydrogen from renewable energy sources. The emissions generated during the construction and upkeep of buses are not included in this study due to the paucity of data sources. However, the majority of the emissions from running the bus and producing fuel are added to the total emissions of the buses

The environmental analysis for the hydrogen trucking project is vital for ensuring the success of this eco-friendly transportation initiative. By rigorously evaluating the environmental effects, our team aims to provide valuable data and recommendations to support the adoption of hydrogen fuel cell trucks in the desired region, contributing to a sustainable and cleaner transportation future.

Safety Concerns and Development

First of all, hydrogen fuel is safer compared to fossil fuel since it is much lighter than air. Therefore, when hydrogen is released, it will rise and disperse rapidly, reducing the risk of ignition at ground level. Moreover, hydrogen also has lower radiant heat than fossil fuel, which means it will have a lower temperature when burning. A higher oxygen concentration requirement is also needed for the explosion, thus, hydrogen will be less likely to explode given the same conditions compared to other forms of energy sources. Even if there is an explosion, the concentration will decrease faster as well.

Some examples of accidents that happened in the past include 1) A pick-up truck and trailer carrying large cylinders of hydrogen crashed and exploded in Ohio in February 2023, About 30 seconds after the crash, a wave of explosions began as 420 kg of hydrogen, carried in six large cylinders, started to burn. 2) A devastating hydrogen tank explosion occurred in Gangneung, South Korea. It was a testing site and the hydrogen was produced by the water electrolysis. Two men died in the accident. Several buildings, including the ones that are 100 meters away were damaged.

For storage, we will store hydrogen in special tanks that can handle high pressure, and these tanks are made to be strong and safe. However, it's still important to follow strict safety rules when handling, transporting, and storing hydrogen to prevent any accidents. Same as at hydrogen fueling stations, there are strong safety measures in place. These stations are designed to safely dispense hydrogen, and they should have emergency sensors to detect any leaks and then a shut-off system to prevent the leak from spreading. This helps to keep everything safe when trucks are refueling.

The trucks themselves also have many safety features. The fuel cells and storage tanks are designed to be safe, even in case of a small crash. The manufacturers of these trucks did a lot of tests to make sure they were safe to use on the roads. People who work with hydrogens, like truck drivers and maintenance staff need to be trained professionally. This helps them understand how to safely handle hydrogen and what to do in case of an emergency. Emergency responders also need special training on how to deal with hydrogen-related incidents.

In case anything goes wrong, there should be clear protocols and special equipment in place for people to respond quickly and safely. Learning from past incidents involving hydrogen also helps to improve safety measures. Various US departments published their regulations and policies such as the Hydrogen Fuel Cell Engines and Related Technologies Course Manual from the US Federal Transit Administration, the US Department of Energy safety codes and standards, and OSHA and their list of regulations as well.

Conclusion

In closing, our project on sustainable hydrogen for long-distance trucking has been a profound learning journey for us as a team. Throughout this semester, we have immersed ourselves in the intricate world of green hydrogen, striving to understand its role in transforming the trucking industry. Our investigations into the production, storage, and utilization of green hydrogen, underpinned by rigorous modeling and analysis, have not only broadened our technical knowledge but also deepened our appreciation for sustainable energy solutions. As we analyzed economic impacts, environmental benefits, and safety considerations, we recognized the

complexities and potential of hydrogen-powered transportation. Our work, though a part of our academic curriculum, goes beyond the classroom—it's a contribution to a critical global conversation on reducing carbon emissions and a testament to the impact that dedicated students can have in driving forward innovative and environmentally responsible technologies. This project has been a blend of challenges and discoveries, shaping not only our understanding of green hydrogen trucking but also our aspirations to be part of a cleaner, more sustainable future.

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