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Module 4 - Conclusions on Hydrogen Train Feasibility & Recommendations

Introduction

Before researching each module we wanted to address our assumptions and misconceptions of hydrogen trains. In module one we understood that addressing the climate crisis requires leaving no stone unturned and needs a high level analyzing and exploration of multiple routes. With the Energy Policy Act of 2005 and the Paris Climate Agreement in 2015, we understood nations are investing in net-zero energy sources. In the transportation section, one serious consideration is the feasibility of hydrogen-powered trains. With the limited time we have, we assumed about industrial rationale, technical feasibility/potential, environmental effects, economics, and policy:

Assumptions and Challenges of Module 1

- *The two biggest problems with implementing hydrogen-powered trains are infrastructure and cost.*
- *Certain forms of hydrogen are not a viable form to utilize for a transition.*
- *While most industries are willing to invest in a fossil-free transition to a certain extent, rail transportation is already low-cost, so there is no financial incentive to switch to hydrogen specifically.*
- *Hydrogen's biggest competitor is electrification (e.g. battery transportation).*
- *Switching to hydrogen will be too complex to implement via governmental policy alone. The private sector/entity is needed.*
- *The traveling and transportation market is at the backbone of the American economy.*
- *Renewables are not yet up to scale for US energy needs.*
- *American railroad infrastructure is not ready for these types of major changes.*
- *The hydrogen trains in passenger cars will only attract middle to high-income users and further inequity unless addressed.*

Assumptions and Challenges of Module 2

- *In the near term, Hydrogen trains can be executed in the US by trying to retrofit current (diesel-powered) trains so that they are hybridized. It can lower the overall emissions of all diesel-powered trains. And since there is existing infrastructure for rails, they can be used as the testing grounds for hybrid trains. For the EU, there have been companies that made efforts to deploy hydrogen trains and successfully create initial versions of their train technology.*
- *In the medium term, the US could deploy hydrogen trains that run on a limited route (where there are hydrogen refueling stations). The EU could deploy more hydrogen trains with better technical quality due to their proactive policies and more remarkable ability to source renewable energy.*
- *In the long term, trains solely powered by hydrogen in the US can be feasible when renewable energy is available to produce green hydrogen grows and costs of hydrogen fuel cells and hydrogen drops (from demand due to other hydrogen applications). For the EU, they could be well on their way for hydrogen trains if they decide that hydrogen trains are the best route for rail transportation.*
- *Hydrogen trains can be a good solution in regions where electrification is not logistically ideal and can allow for better connection of people who are living in isolated regions where electrified rails do not exist.*

Assumptions and Challenges of Module 3

- *Hydrogen trains would be cost effective and their energy efficiency would provide greater value to the rail transportation sector.*
- *There is a challenge of comparing hydrogen to other energy sources (renewable electricity, battery, diesel) because there is complexity in determining the costs of sourcing hydrogen fuel and creating a network for it.*
- *In 2020, there were approximately 28,000 locomotives in the U.S. class I railroad operators fleet, which follows the growth formula of* ***# of locomotives = 323 * (year) - 624350****.*
- *All of the current locomotives in this class need at least one tender car, which makes approximately 28,000 as well.*
- *A diesel locomotive costs approximately $1.5 million*
- *An average U.S. class I freight train carries approximately 8,800 tons or* $1.76*10^7$ *pounds.*
- *A freight locomotive engine outputs approximately 12,000 horsepower to account for improvements in efficiency and the normal range between 4,000 and 18,000.*

- *Prices of a PEM fuel cell/electrolyzer and lithium ion batteries will change linearly over time.*
- *There is a $300,000 cost for a hydrogen locomotive structure and $1 million for an electric locomotive structure.*
- *Pressurized gas hydrogen tanks cost approximately $15/kWh.*
- *The structural cost of a hydrogen "tender" car is $150,000.*
- *The Class I network in the U.S. contains a constant 92,282 miles of track to be electrified.*
- *It costs approximately $2.5 million to electrify a mile of track.*
- *After 5 years of additional aggressive R&D, the conversion rate of either transitioning from diesel to hydrogen or diesel to battery starts in 2026 at 5% and incrementally increases by 5% every 5 years.*
- *With the cost of PEM electrolyzers/HFC in $/kWh being $1182/kWh in 2020 with the projection to be $1065/kWh in 2025 and $737/kWh in 2030, the future model follows the formula* ***$/kWh of HFC = -44.5 * (year) + 91107****.*
- *With the cost of batteries in $/kWh being $156/kWh in 2019 with the projection to be $109/kWh in 2023 and $51/kWh in 2030, the future model follows the formula* ***$/kWh of battery = -8.29 * (year) + 16885****.*

The Value of Hydrogen

For hydrogen trains to be an attractive step for short-term governmental support and long-term support from private train corporations, a good core value proposition needs to be developed. Firstly, hydrogen application in trains is highly relevant to today's political and social climate-conscious climate. There is a widespread understanding that as the world's energy consumption is projected to rise by 50% by 2050 alongside net-zero targets, changes in the sources and carriers of energy must change. As a result, consumers continue to make more climate-conscious decisions alongside industries being pushed to do the same. Additionally, a switch to hydrogen is feasible in this environment as many banks and organizations offer sustainable finance solutions/transitions. The quantified value of this method comes from the multistage system of initial financial support/encouragement. As with renewable energy, there is a likely projection for hydrogen production costs and transportation to drop significantly as a result of R&D and advancements within other industries. While green hydrogen solutions don't support renewables at this point, the projection of growth of renewables coupled with the development of hydrogen production/fuel cells unveils its long-term competitive advantage compared to alternatives. This reigns true when it comes to hydrogen's ability to run for significantly longer distances than other options. Differentiation of choosing hydrogen comes through selecting the regions/applications with the most significant probability of succeeding long-term. Ideally, this would be in locations that are harder to electrify, easier to store hydrogen within, ideal for harvesting hydrogen in, and conveniently close to growing renewable energy sources. Choosing trains that would benefit the most from this technology, such as freight trains, would provide market differentiation and promote hydrogen to specialize in heavy, long-distance transportation that extends to other modes (e.g., ships, airplanes, etc.). The utilization of different transport methods also exponentially increases the advancement/efficiency of the technology as there are more R&D investments.

Circumstances that hydrogen has competitive advantage over alternative power sources

In order to assess the steps needed for hydrogen trains, we need to understand what circumstances would allow hydrogen to have the competitive advantage over alternative power solutions.

Alternative #1: Electrification of line

From an emissions standpoint, electrification and hydrogen (gas form) come head to head in merit, but emissions benefits of hydrogen only apply if the hydrogen used in the train is green hydrogen. Electrification is currently considered one of the most energy-efficient and safer options than battery, diesel, and hydrogen train cars, making it an appealing choice for implementation in rail lines. However, the economics and overall value of electrification (assuming electricity produced comes from renewable energy) are not as high as hydrogen due to the amount of capital investment that is being poured into hydrogen technologies because hydrogen has great potential to become cost-competitive. Another benefit of exploring hydrogen train technology is that it can fill the gaps for clean transportation in regions where electrification is logistically challenging.

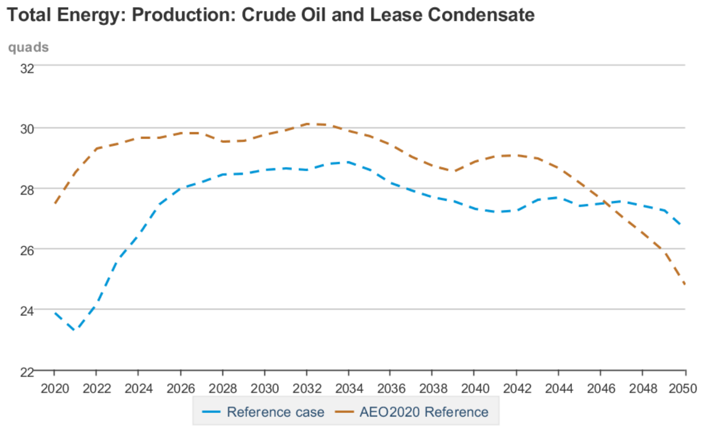
Alternative #2: Battery

Along with electrified train lines, battery-powered trains do not have significant safety concerns. Compared to electrification and hydrogen, batteries do not do as well in terms of long-range performance. While batteries may work well for passenger trains, they would not sustain the train for long periods; battery trains can only cover 120 km per charge while hydrogen trains can cover 1000 km per refueling. One important factor is that batteries are a necessary component of hydrogen trains' traction systems, which use batteries to temporarily store energy created by the hydrogen fuel cell. This means that the success of hydrogen trains will also have to rely on battery technology's success. As of now, researchers can develop batteries that are more energy-dense and compact than ever. Suppose such batteries are utilized in the design of hydrogen trains. In that case, they will boost the energy efficiency of hydrogen trains significantly.

Another essential thing to note is that the cost of replacing diesel trains with battery-electric multiple unit passenger trains (EMU, trains that have rechargeable batteries and are connected to overhead wires) is significantly lower than that of hydrogen. Battery EMU trains (from Alstrom) cost 35% less than hydrogen trains. They are more energy-efficient than hydrogen trains since their energy demand ratio (from the grid) to the power required to move 1.2:1. Meanwhile, the proportion of energy demand from hydrogen (from performing electrolysis) to the force required to carry is 3.4:1. In the case of passenger trains, these current comparisons show how hydrogen technology will have to scale up to match the cost and energy efficiency of batteries.

Alternative #3: Diesel

Diesel is an insecure choice due to its future projections in governmental, industrial, and net-zero global trends. As a result, changes away from diesel-powered trains can already be seen in Europe as aggressive action targets decarbonization of transport. Operators continue to look at alternatives that don't rely on diesel for trains. In North America, diesel still dominates without significant resistance. However, a change in political leadership has called for a spark in "the second great railroad revolution, according to Joe Biden. To ensure safe, clean, and fast rail systems "for both passenger and freight." It is projected that trains in the United States will start undergoing a significant change. Because of this, the use of crude oil is projected to drop near pandemic levels by 2050.



Source: U.S. Energy Information Administration

By analyzing the alternatives above, we can see that hydrogen has the potential for a significant competitive advantage within the training industry going forward.

Current State of Relevant Energy Technology

With the increasing need for low carbon energy solutions and the electrification of the grid, many countries are turning to renewable energy sources and alternative fuel sources to meet their demands. It is important to note that wind and solar (PV) are dominant amongst all renewable energy sources and that they will be responsible for powering a large portion of the electric grid. Over time, the energy capacity of technologies such as wind and solar has increased and significantly lowered the cost of "clean" electricity and they will continue to increase their capacity over time. As of 2020, the lumped transmission capacity for these two renewables (in the US) is ~320,000 GW and with the projected $3.2 trillion investment that will be made in 2050, the capacity has the potential to be ~1,012,000 GW. While heavy investments in renewable energy demonstrate a commitment to green electric grids, in an ideal situation, wind and solar need to have a 5.7 TW capacity for the US to be run on 100% renewable energy, and we are far from this goal. Current renewable energy infrastructure within the US has not been expanded enough to be able to meet demands of the electric grid and will require 10-30 years to increase their capacity.

In relation to the rise in renewable energy, more organizations have become interested in alternative fuel sources such as hydrogen and have identified it as a potential means of powering multiple parts of the transportation, industrial, and building sectors due to it being able to address carbon-intensive processes that normally can only run on the energy produced by natural gas/fossil fuels. On the transportation side, hydrogen powered vehicles such as cars and trains are able to run longer than their battery-run counterparts and they hold an advantage over regular gas or diesel vehicles due to hydrogen fuel's high energy density.

In order to evaluate the reasoning behind the interest of developing hydrogen fuels, it would be beneficial to understand how hydrogen works. There are three types of hydrogen: (1) Gray hydrogen: Chemical processes to derive H_2 release emissions into the atmosphere, (2) Blue Hydrogen: Uses Steam Methane Reforming (SMR), Autothermal

Reforming (ATR), and Industrial feedstock are coupled with carbon capture, usage, and sequestration (CCUS), and (3) Green Hydrogen: Since it uses 100% renewable energy in electrolysis procedures, it will heavily rely on renewables having high energy output and low costs. Blue hydrogen is currently the most cost effective hydrogen production method, which can help drive down overall costs of H_2.

Reason for Hydrogen Usage:

Development of hydrogen technologies can be justified by the variety of applications hydrogen has. It can be used for: long-distance, heavy duty vehicles, ships, high grade heating for industrial machinery, steel processing, chemical processing, etc. Regarding vehicles, many may bring up batteries and electrification and discuss how it has been effective in making the transportation sector “cleaner”. Though it is true that countries have been able to take steps to further application of batteries, and use it to address needs to electrify certain sectors (i.e. privately-owned or light-duty commercial vehicles), they are not the end all, be all solution to clean transportation. Batteries have their own issues such as: charging time, damage from repetitive recharging, batteries’ toxic leakage, the demand it creates for precious metals (lithium, cobalt, etc.), their sensitivity to cold temperatures, reliability for travelling long distances, etc. The issue that stands out the most from batteries is that they are not reliable for travelling long distances; this is due to the need to charge and the battery’s energy density. Hydrogen can fill the gaps of batteries. Because hydrogen is a very energy dense fuel, once its energy is harnessed by hydrogen fuel cells, the vehicle/process relying on the fuel would be able to run for significantly longer AND can yield enough energy to power heavier equipment and vehicles.

Hydrogen Fuel Cell Types:

The current fuel cells technology available are: (1) Alkaline Electrolyzer (AE), which is an established, but costly technology that has efficiency and limited electrolysis density, (2) Polymer Electrolyte Membrane (PEM), a technology that is expected to become lower in cost compared to AE, but requires more R&D to make possible, and (3) Solid Oxide Electrolyzer (SOE): newer technology that uses simpler method than PEM, and can perform high efficiency electrolysis compared to PEM & AE (also requires more R&D). By 2025, the CAPEX for AE and PEM is ~$1065/kW and the CAPEX for SOE is ~$1075/kW. Assuming OPEX is ~$40/kW, If a H_2 production site has a 1 MW capacity, by 2025, the cost of producing H_2 in a year is ~$15.5665 b/MW for AE & PEM and ~$15.675b/MW for SOE.

Given the high costs of hydrogen fuel cells, more investments should be made to produce BOTH Blue H_2 and Green H_2 so that R&D for electrolyzer technology, etc. can continue iterating while Blue H_2 production increases the availability of H_2 to us. Raising H_2 capacity can ultimately lower costs and create a demand for fuel cell manufacturing.

Hydrogen Storage & Transport Network

One of the biggest concerns related to the feasibility of deploying hydrogen power is the cost of hydrogen storage and transport. Currently available technology such as cryostorage and liquid organic hydrogen carriers aim to liquify hydrogen into its compressed form. Because cryostorage requires large amounts of energy to maintain hydrogen in its liquid form, more research has been done on taking advantage of underground storage and liquid organic hydrogen carriers. While researchers still need to address issues with hydrogen leaking from the storage or creating poisonous chemicals with the materials located in underground storage, liquid organic hydrogen carriers may provide a good solution to cost effective storage and transport. Liquid organic hydrogen carriers are ideal due to their ability to be transported through our existing natural gas pipelines. In addition to the use of pipelines, liquid organic hydrogen carriers also allow for transport of hydrogen through truck fleets, which already exist for natural gas distribution. However, the success of using current infrastructure and methods for hydrogen storage and transport will come at its own cost; more research will have to be done to prevent hydrogen leakage through pipelines and hydrogen transport containers.

Global Perspectives

Power Generation & Consumption

For countries on the journey to reach net zero by 2050, the IEA projects that the amount of renewables in their total electricity supply needs to be 60% in 2030 (as of now we are at 27% energy shares) and the remaining individuals who use fossil fuels and coal are expected to couple CCUS technology with their energy plants. The total transportation power consumption of countries who’ve declared their carbon neutrality goals is ~2500 Mtoe (which is 1.0467 x 10^{20} Joules) of power, and other heavy-carbon emitting sectors such as industry and buildings have power demands of similar magnitude. The issue that the world now collectively faces is that global energy consumption will exponentially increase over the years, and add to the rate in which CO_2 is emitted. In the next 30 years, governments will need to find effective strategies and clean energy technologies to cut emissions across all sectors while also meeting the increased demands for power. And their efforts towards electrification and clean technologies will require billions of dollars in investments.

The Electric Grid

The electric grid started as an innovation and improvement to the infrastructure and industrial sector with power stations, train stations, and dams. In recent years, the push to the electrification of non-electrical grids and vehicles has been a priority for countries and cities due to the push for sustainability and environmentally aware consumers and regulations. In Europe and specific to trains, The United Kingdom has 42% of its train routes electrified, 61% Spain, 71% in Italy, and 100% in Switzerland. To scale it down, typically in the mainland of Europe, it costs $965,000 to $1.3 million to electrify one kilometer's worth of track. As we compare this to other energy sources, electricity is here to stay. It will most likely be incorporated in any changes from less sustainable energy to higher sustainable energy.

The Transportation Sector

The transportation sector has a wide range of scale, from scooters to transportation craft. A common thread among these vehicles' evolution is the energy used to power them due to developing technologies, financially and environmentally aware consumers, and the overall cost-benefits. Concerning hydrogen, planes, trains, and cars have some attempt of having a hybrid or full use of it. There have been tragic incidents of using hydrogen in planes. In contrast, cars and trains had more success with safety and its implementation. As safety narrows down what vehicles in the transportation start converting to hydrogen, there is an overall transition from diesel to zero-emission transportation on a city, regional, national, and international scale. This rapid change forces countries to confront their dated infrastructure and improve it for consumers and save operation costs. This confrontation of old instruction brings out systematic issues on how the country handles change in the private and public sectors; by addressing the need to develop new infrastructure as each energy source requires different needs to be maintained. Since electrification is not always cost-effective, countries looked towards alternatives like renewables and hydrogen. The increased interests allowed private companies to develop technology to meet countries' needs and match or exceed diesel and electric-powered trains. Like many other sectors, the transportation sector is adapting to rising demands to address climate change and take advantage of new technologies and implementations of energy.

The American Railroad System

Given that America's railroad system is not only the largest, most diverse in the world but also privately owned by approximately 630 companies, it's clear to see that rolling out such an industry-wide change is not going to be a walk in the park. A for-profit, long term approach must be taken when addressing a need for this change. This is already different from other countries which contain publicly or state-owned corporations. On top of this, most railroad infrastructure, workers, and mileage are involved within Class I railroads, which involve long-haul freight trains that are crucial supporters of the economy. Most of these rail lines are split up into passenger rail lines, which run on a blend of mostly diesel and some electric powered lines (<1% of U.S. railroad tracks), and freight rail lines, which only run on diesel. Economic and technological regulation throughout the industry plays a huge role in designing retrofits and implementation potential, especially as it is much more difficult for the U.S. railroad companies to finance electrification upgrades than to build diesel-fueled systems. Considering this, important questions were brought into play as to what design solution would be the most feasible. For example, can one trust to store hydrogen underneath the train car, in the car with the passengers, or at the roof of the train car?

However, one of the most important challenges faced when trying to assert governmental intervention within freight railroads is the partial economic deregulation managed by the Surface Transportation Board (STB). The STB maintains the current regulatory framework and resists the implementation of significant changes that would detriment the industry's revenue needed to reinvest, maintain employees, and meet customer demand.

Economically, these railroads support approximately 11 million jobs and generate $220 billion in economic activity with $26 billion in tax revenue. Applying hydrogen fuel cells (HFC) on a regional scale, throughout freight transportation alone, would affect the industries to which they serve. Applying it throughout the passenger sector would affect the pricing of transportation for those regions as well. However, this route is not favorable for a number of reasons: the initial cost is passed onto consumers, hydrogen is more effective at transporting heavy payloads such as goods transported by freight, and electrification is already being implemented in passenger transportation to a small degree.Therefore, the initial phases of transition should be focused on freight transportation alone. Understanding the technological needs of these types of railroads as well as the financial support needed from suppliers is vital to a holistic energy redevelopment plan, regardless of power sourcing.

Debunking Rebuttals

Hydrogen as an energy source has never been the most ideal. It has come with its weaknesses and failures. Skeptics cite current inefficiencies, high costs, lack of implementation, and past failures as reasons to not pursue hydrogen power, let alone in the railroad system. However, the idea that you try something once with a lack of success and immediately run away is pointless. Things might seem as if hydrogen power might always be behind the curve and constantly need extra support, but we must remind ourselves that all of the renewable technologies today faced the same types of criticism 20-25 years ago. Does that mean we should not have supported them to bring them to the level, price, and availability they are today? We don't think so.

Just like has been proven effective with renewables making their debut in the market today, the same could be applied to the progression of hydrogen to expand it past a strong governmentally led R&D stage to a strong industrially led commercialization stage. To ensure this, the following components would be ideally included:

- Investment into R&D through grants
- Feed in Tariffs throughout industrial applications
- Governmental programs to build or abate infrastructural development
- Federal tax credit on railroad corporations and suppliers developing initiatives for hydrogen fuel-cell trains
- Training programs to ensure it is used with proper safety and environmental controls

Another source of skepticism arises from hydrogen's issue with storage, as outlined above. Because hydrogen can only be stored in cryogenic temperatures or highly pressurized tanks, skeptics not only deem the technology unsafe but unrealistic for large scale practices. By their nature, all fuels have some level of danger accompanying them. While there are some significant properties of hydrogen that make it more complex to implement engineering controls to ensure safety, it is still a reasonably safe fuel to work with because of its simplistic, non-toxic properties and the state of other forms of fuel today. However, the low risk of electrified tracks in comparison makes it seem unattractive as a competitor. One solution that counters this and the need for a completely revamped natural gas pipeline is the use of liquid organic hydrogen carriers (LOHC), which allow for hydrogen to be stored and transported in a stable state at room temperature and do not require as much energy needed for cryogenic storage methods.

One major source of skepticism lies within hydrogen's capability of remaining net-zero while increasing affordability. As most hydrogen production today is gray with sourcing from fossil fuels, how is the transition to a net-zero hydrogen source going to be possible when green hydrogen is too expensive? This answer lies within blue hydrogen, an intermediary form of hydrogen production that involves economical retrofits of existing gray hydrogen facilities. More importantly, it spurs the coexistence of advancement and innovation of Carbon, Capture, Utilization, and Sequestration (CCUS), which is based off of a well established technology (CCS) but supports a circular carbon economy. Instead of industrial reluctance for the extra cost of cleanup with CCS, a market can be created for economic incentive for using this technology. Until costs of implementing CCUS systems within the energy sector go down over time, certain production tax credits that provide financial returns for not emitting are already in place, such as the 45Q.

The Reason Behind Implementing Hydrogen Trains

The talks about hydrogen trains speak to a larger conversation that the transportation sector is modernizing its systems. This means that a train's lifetime can be extended by a generation and stay up to date with current regulations and technologies. This trend is due to an increase in people moving to cities and increased demand for accessing cities. This demand has different implications on different scales such as:

- A City requires the system to handle a high capacity and high frequency of trains coming in and out.
- The regional level requires the system to have more extended durability, up-to-date signal, and a comfortable and safe experience for the customer.
- Continent scale demands a full service and maintenance system to endure the weather and train carts that can be energy efficient and have less pollution.

It can be addressed first at a legislative and investment level. Afterward, it trickles down to updating the infrastructure such as signaling and components. Depending on the company, the train (new and/or retrofitted) is put into current routes and services. Finally, the rail line adds any necessary and permanent infrastructure like power stations. Hydrogen itself has a competitive advantage over alternative power solutions because the technology is more developed compared to solar or wind & is being heavily invested in compared to solar or wind. Hydrogen is a tangible next step from diesel and even electrical, whereas solar or wind is not comparable yet due to the lack of advanced technology.

Logistics of Implementing Hydrogen-Powered Trains

To break down how hydrogen-powered trains can be rolled out, we need to understand where, how, when, and what needs to be implemented at different long-term operation stages.

Locations for Hydrogen-Powered Trains

While the United States has the largest rail network globally, its passenger network is minimal compared to other European, Indian, and Japanese countries. Considering this and hydrogen optimal efficiency with heavy loads and long distance, freight trains within the United States seem to hold the biggest potential for hydrogen-powered trains. This is especially true as the United States network is in the highest need of a transition from diesel powered freight trains.

Existing gray hydrogen facilitates

Understanding the location of major rail lines related to existing gray hydrogen facilities is key for picking the ideal location to first first implement hydrogen trains. As the major production facilities are in California, Texas, and Louisiana. However, most of these sites produce hydrogen close to their end use (large industrial sites). These facilities can serve as the first retrofitted carbon capture, usage, and storage (CCUS) prototypes to create a close to net-zero hydrogen source. Once more R&D develops more effective distribution/transportation systems for hydrogen, they can be utilized within the rail network in freight stations nearby.

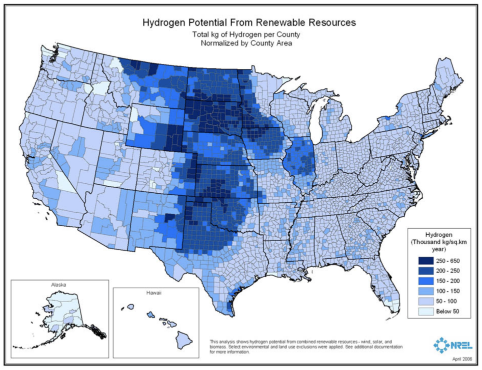
The Sectors to Implement the Trains

Alstrom's approach to hydrogen trains varied per region due to the different levels of infrastructure. For example, in America Alstrom mainly focused on services such as signaling, repairs, and maintenance. On the other hand, in Europe Alstrom fully implemented the hydrogen train and power stations. The key difference is that each region has different developed infrastructure levels, which means a different approach to a solution. The current technology in passenger trains, freight trains, and locomotives differs in addition to the different levels. Depending on government support and goals of improving their rail infrastructure, Alstrom stepped in accordingly.

Hydrogen Potential within US

Renewables

For hydrogen trains or hydrogen applications to be genuinely "zero-emissions" and green, the energy used to produce hydrogen through all methods (steam methane reforming and electrolysis) will need to be powered by renewable energy. When looking at the feasibility of a hydrogen-powered train, one needs to consider the high costs of green hydrogen. The current capacity of the different types of renewable energy and the US's deployment plans for the next few years do not seem to be moving as fast as those of other countries. It would be advisable that hydrogen manufacturing sites be placed close to renewable energy power plants (see map on the right). In connection with the siting of (new) railways for hydrogen trains, it would be logical to site hydrogen refueling stations closer to regions where there is a high concentration of renewable energy sources to lower hydrogen transport costs.



Water source

One consideration to make about the mass deployment of hydrogen production is that sitting for most of the production facilities for both blue hydrogen (from steam-methane-reformation) and green hydrogen will need to be in regions that contain large amounts of high purity water. Approximately 9 kg of high-purity water is required to produce 1kg of green hydrogen. While processes such as reverse osmosis can produce water feedstock for hydrogen production, such processes create additional steps to the hydrogen production process, furthering the production complexity and incurring higher costs for each kg of hydrogen produced. In the near term, most hydrogen production facilities will have to be placed in regions with reservoirs containing high purity water (i.e., the Midwest, Mountain States, and West Coast in the US). Consequently, it would be most logical to site hydrogen train lines in regions where high purity water is available. Since clean water is an essential resource for all, areas that have limited water supply may not be able to implement hydrogen technologies until solutions such as salt-water electrolysis are further developed and scalable. Current research efforts to overcome this issue demonstrate that there are opportunities to further branch out hydrogen train lines to regions that are not the most ideal for hydrogen production in the future.

Network potential

One needs to look at building out a strong hydrogen network, where regions with existing rail infrastructure have no way of setting renewable energy plants and hydrogen manufacturing plants nearby. One good option for hydrogen storage and transport would be to utilize the existing gas pipeline infrastructure and the transport system. While it would be ideal for transporting pure liquid or gaseous hydrogen to refueling stations, it is unstable. It could be better transported while stored in liquid organic hydrogen carriers (LOHC: i.e., Ammonia, Methanol, Toluene). However, one issue that LOHC presents is hydrogen leakage and the damage it can cause to the materials of the current pipeline. Not only do LOHC's allow for stable storage and transport, but they also offer a means of transitioning the use of our natural gas infrastructure into a low-carbon energy mode of transport. In this case, it will be necessary for the government and other organizations to fund research for low-cost chemical processing for hydrogen compression and design permeation-proof materials.

In terms of storing LOHC's, they could be effectively stored in regions that have depleted natural gas, oil reserves due to their similarities to crude oil. This can allow for greater cost savings for storage. One point that must be acknowledged is that there is little research done on the potential environmental hazards (toxicity & biodegradability) of LOHC's. Another point to acknowledge about the application of LOHC's is that there is also little research done on systems (i.e., engines, etc.) that can leverage the energy produced by LOHC's through chemical reactions, as they require specific amounts of heat and catalyst to react effectively. Despite the current research gaps, the interdisciplinary collaboration will allow for such a storage and transport system to come to fruition.

In addition to the use of LOHC's, direct storage of hydrogen in salt caverns and hard rock caverns are appealing for storage due to their low hydrogen permeability. And they can be cost-effective storage methods for hydrogen for regions that contain them. The issue with such geological formations is that they are limited by location, meaning the price of hydrogen fuel increases the distance away from the storage site. There are inefficiencies/difficulties in implementing systems of hydrogen fuel storage and transport. Still, it is now necessary to look for zero-carbon solutions (with the promise to reach net-zero). Some researchers have been continually working to address all types of hydrogen storage issues in the past decades.

More recently, there has been a technological breakthrough called POWER PASTE. POWERPASTE is a paste-like substance made out of a magnesium hydride base. It can address hydrogen storage, transport, AND safety concerns. With its stability in temperatures up to 250 °C degrees, the chances of explosion or chemical reactions during transport or usage in vehicle fuel cells are very low. And with its high energy density that is ten times that of batteries, it can present hydrogen as a highly competitive zero-carbon fuel. While POWER PASTE is in its beginning stage of research, these discoveries prove that with research and funding, hydrogen technology can become a reality.

Hydrogen's Competitiveness Considerations Internationally

With the 2015 Paris Climate Agreement pushing for net zero emissions by 2050, this change's main hubs are in Europe, Asia, and partially North America. Most trials and implementation of hydrogen trains started around 2017 in Germany and France under the company Alstom. A primary reason for the start of this research and the execution of hydrogen fuel cell (HFC) trains is legislation within the country and their timelines in reaching the Paris Agreement. In EuroAsia, the focus of HFC is passenger trains and putting the user as a priority such as safety, noise, experiences, accessibility, and convenience. Considering these case studies and plans for implementation, we think hydrogen-powered trains can be competitive to diesel and potential electricity depending on how it is applied. The case made for HFC trains are: that it can operate on non-electrified lines which allow accessibility for the passenger in rural and less used stations, it is much quieter compared to other types and make it desirable to live near the station, financially comparable to overhead electrification in a lifetime cost, and is faster to travel by train due to its speed.

Particularly in Scotland, United Kingdom, and China, the goals of trialing these trains range from 10 months to 24 months. These goals allow diesel trains to be taken off the rail system and replaced with HFC trains while meeting the same performance. Examples of these performances are the amount of passengers, city and regional distances, speed, and frequency. The hydrogen train company, Alstrom, is responsible for much of this change in Europe and Canada. Their trains can go 160 km/h on a regional scale and 200 km/h in a city. Their approach to switching to HFC is: creating a new train itself, storing hydrogen on top of the train, away from passengers, targeting locations and rail lines that are more cost-friendly compared to electrical, and having a massive presence in discussions of global transition away from diesel. In the coming months, the next phase of Alstrom's reach in the industry changes from portable charging stations to permanent stations along with Europe. Unlike Alstrom, Porterbrook is another train company that focuses on retrofitting older trains into hydrogen-fueled power systems. This tactic cut costs while fitting into the train infrastructure's physical spaces since most tunnels and lines date back to the Victorian Age. Overall, Europe has been ahead of the world in the number of trains converted to HFC and increased interest from the public by targeting passenger rails.

Unlike the examples we mentioned in Eurasia, HFC trains in the United States of America would likely occur in freight and goods transportation first before passenger trains. This user change is due to the freight trains having the 70% majority of using the rail infrastructure and the US's different culture with a low interest in passengers traveling by train. However, some moves in smaller cities and regions increase passenger train usage through electrification of some rails and decreasing traveling time between cities, like Las Vegas to Southern California. As freight trains seem to be the U.S.'s future, powering them will be more physical and technologically different and challenging. Unlike the US, Canada has different plans for developing its rail line in the coming years with 2025. Metrolinx, a train company, talks with Transport Canada and Alstrom to create the world's most extensive hydro trail starting in Toronto and moving along the coast. Like Eurasia, this push for transitioning comes from the Paris Climate Agreement and other legislation to have these zero-emission initiatives by 2050 and take advantage of newer and more efficient technologies and energy compared to diesel, which justifies why hydro rails are competitive due to the rising demand.

In the long haul, other countries like Japan and Korea have been slowly tackling their transportation sector and moving to more hybrid energy use with electrical and HFC. There has not been much news or official statements about moving to zero-emissions in terms of other regions like Latin America and Africa. Nevertheless, Alstrom has undoubtedly gained a vast reach in Europe and partially North America. There have been talks about being the first to introduce HFC trains into these regions. Again, as the countries we previously mentioned will incorporate hydro rails, the demand, technology entirely, and cost will be more accessible to countries that do not have the same budget and priorities as Europe. With the Paris Climate Agreement goal for 2050, we predict that hydrogen-powered trains will be a better alternative to diesel and other energy.

Process on Implementation

Legislative & Investment

After choosing the location and parts of the train infrastructure to implement the hydrogen trains, understanding how it will be enforced first comes through routing proper financial support and incentive. Just like it has been proven effective with renewables making their debut in the market today, the same could be applied to the progression of hydrogen to expand it past a vital governmentally led R&D stage to a substantial industrially led commercialization stage. To ensure this, the first significant step would be to utilize governmentally funded grants for R&D as it relates to hydrogen production, delivery, and storage. Funding for such contributions would be rerouted from the approximate $4.9 billion/year in direct fossil fuel subsidies. Financial support such as federal tax credits, economical treatments for royalties, passive losses, and capital depreciation allowances should be applied to hydrogen production facilities and suppliers on a short, medium, and long term basis.

Additionally, to support the long-term goal of blue to green hydrogen production, feed-in tariffs need to be maximized to the renewable energy field. In the short term, the government should build supportive infrastructure but should abate private infrastructural development for a long time. To ensure safety with new standards compared to conventional fuel sources/carriers, training programs should also be promoted through governmental funding that allows employees to use proper safety and environmental controls.

Working with governments and local institutions is crucial in executing the plan. In the public sector, we would engage with the Department of Transportation, Department of Energy, and local universities specializing in product design and sustainable energy studies to help develop the four parts of the train infrastructure. Additionally, with local connections, we can better understand what the consumer wants in their experience in taking the train and understand the regions and/or country's goals in moving away from diesel and electrical systems. We would seek private companies and banks that already have a focus or commitment to zero-emission transportation and/or general sustainability goals in the private sector. These partnerships would assist with investment and funding the R&D as well as the implementation of the hydrogen trains and the corresponding infrastructure.

Which Part of the Train Infrastructure are we suggesting

When seeing the train infrastructure, we recognize the four main parts of the infrastructure: rolling stock and components, signaling, services, and systems. The rolling stock and components are the most public-facing since they involve train cars, locomotives, and physical rails. It is important to note that these parts vary in the scale used and the frequency these components are used in, meaning daily, monthly, and quarterly. The signaling, services, and systems are the behind-the-scenes pieces that mostly the company deals with on a regular basis. This involves the marine center, repairs, and electrification of the infrastructure. These parts are equally important to the rolling stock because it needs to be up-to-date and compatible when the hydrogen-powered trains are put into service. Like Alstrom's approach, a robust and well-rounded solution is to work on all these four parts simultaneously with solid legislation, R&D, and circulating into the existing system. We recommend focusing on upgrading the signaling and services to handle the upgraded rolling stock and systems.

Operational and strategic risks for intervention and collaboration

Once the partnerships, investments, and specifying the goals of implementing hydrogen trains are established, the following has to be considered:

- Impacts of COVID-19/current climate status
- Contracts with the partnerships
- Logistics for sourcing the materials
- Risk management with security, accidents, technology, and performance
- Following ethical regulation with internal and regulations adults

These are some aspects Alstrom is concerned with when taking up a project. Using Alstrom as an example, we want to focus on the legal and ethical contracts with these partnerships, risk management of the project, and the logistics of sourcing the materials.

The Timeline of Implementation

Using Alstrom as a precedent study, it took the company three to five years to fully implement hydrogen trains on a suburban and rural scale. For example, in Germany and France in 2016, they made announcements about upgrading the track to fit Alstrom's train carts. By February 2021, they are finalizing permanent power stations for the train carts. This timeline comes with heavy government legislative support, investment, and private sector R&D. Particularly in Europe, there has been a competition to reach zero emissions. Thus Alstrom delivered on the consumer's timeline. This legislation has been backed up by heavy investment when Alstrom received 8.3 million euros. The three to a five-year timeline is when all conditions are ideal, yet this may not be the case in other regions. We suggest that there needs to be more development in the technology and a deeper investment in the project from countries. As an example, the U.S. and Korea do not have strict or defined timelines to have zero-emission transportation. Thus the development and execution of hydrogen trains in the passenger and freight sector may not fit the three to five-year timeline that Alstrom provided in Europe.

Since we want to focus on the U.S. and input from over 20 international energy/technology companies, our team was able to assemble a timeline based on attractive industry transition goal:

2022 - 2030 - Expeditious Next Steps

To start off on the right foot, the next 2-3 years should include three main actions:

1. Initiating reliable and technology-neutral decarbonization objectives in the federal and local (state) spheres. This crucial step serves to shepherd specific regulatory actions and policy, which can potentially penetrate private rail corporation spheres.
2. Focus on the most attractive solutions, segments, and locations to prototype and prove hydrogen-fueled trains' efficacy. This considers the previous information within this report of choosing the “where” and “how.”
3. Scaling and providing governmental financial support for further R&D of mature, applicable applications (e.g., natural gas reforming, on-site water electrolysis, CCUS). This opens the door to cost reduction and performance improvements in the future.

Such actions will increase hydrogen-based technologies' awareness and build a more broad acceptance as it continues to develop and prove itself. This is essential to make within rail industries as the following stages are carried out. Observing the growth, successes, and potential of hydrogen as a driver for the American freight industry convinces these private corporations of hydrogen trains’ value proposition.

2031-2040 - Preliminary Scale Up

This step mainly brings hydrogen costs down as demand increases and hydrogen production has promising large-scale projections. Through policy support, hydrogen-based technologies will be heavily considered or preliminarily implemented throughout different industries outside of trains. This will encourage the economic improvement of large-scale hydrogen supply and end-use equipment. This stage functions as a driver for critical infrastructure to be put in place for long-term implementation.

2041-2050 - Diversification

As the success of hydrogen within the rail system of America depends not only on its implementation in the rail industry, this step is especially important. This stage is focused on expanding hydrogen past the early-adopter/prototyping segments. With the continued growth of renewables, transitions from blue hydrogen to green hydrogen can start being considered and implemented in ideal areas. Potentially, exporting hydrogen, associated equipment, and storage materials can also be considered at this phase as national growth of hydrogen based technologies continues.

Post 2050 - Aggressive rollout across the United States

At this point, applications of hydrogen can be distributed on a larger scale. For trains, this would mean larger Class I rail lines implementing hydrogen power. Here, the lowest-cost solution would be applicable compared to other alternatives. This would attract more investments to grow the technology and cost-effectiveness further. A robust hydrogen code should be built at a federal level standardizing practices across the country for further deployment.

Sourcing Hydrogen + Costs

The cost analysis of hydrogen sourcing is conducted by treating hydrogen like a fuel source: According to Sandia National Laboratories study conducted in 2017, the cost of hydrogen from stations with 100 kg/day capacity are:

- $30.05/kg (when delivered from an H2 production facility)
- $38.47/kg (for on-site SMR produced hydrogen)
- $39.66/kg (for on-site electrolysis produced hydrogen)
- $29.12/kg (for hydrogen delivered to a modular H2 station).

From comparing these values, the study determined that the cost of having hydrogen delivered to hydrogen stations is much lower than having hydrogen stations that are on-site of hydrogen production facilities. And it also pointed out that modular hydrogen stations (which act as small hydrogen storage units and in some cases can also produce hydrogen) can lower costs of hydrogen for users significantly due to the reduction of necessary equipment sizes and transport tank sizes. Assuming that a city requires 50,000 kg of H2 per day for all applications, the total cost of a conventional and modular hydrogen refueling station that get hydrogen delivered (including station installation cost) are:

Hydrogen Station type	100 kg/day	200 kg/day	300 kg/day
Conventional Station: Delivered H2 from production facility	$3.04M	$2.61M	$2.57M
Modular Station: Delivered H2 from production facility	$2.82M	$2.20M	$1.99M

Due to the technology and equipment SMR requires, it is more costly than electrolysis and it can also incur higher costs due to its carbon emissions (See table below). If one assumes there is a carbon tax of $4 per ton of CO2 emitted, 50,000 kg of SMR-produced hydrogen would incur a $2,152.96 carbon tax. And SMR with a carbon capture system will incur a $977.28 carbon tax, since not all emissions could be sequestered.

Hydrogen Station type	100 kg/day	200 kg/day	300 kg/day
Conventional Station with on-site Regular SMR Hydrogen (Original cost of hydrogen in brackets)	$4,824.28 ($3,847.00)	$7,344.96 ($5,192.00)	$8,221.96 ($6,069.00)
Conventional Station with on-site SMR Hydrogen and CCUS technology (Original cost of hydrogen in brackets)	$4,824.28 ($3,847.00)	$6,169.28 ($5,192.00)	$7,046.28 ($6,069.00)
Conventional Station with on-site Electrolysis	$3,966.00	$5,302.00	$6,522.00

While electrolysis-produced (green) hydrogen is lower in cost, it still remains costly due to the fact that it requires clean water sources, and a lot of electricity. While there were concerns of the cost of renewable electricity in 2017, the cost of electricity from solar and wind are now competitive with the price of gas-produced electricity, which has a median cost of $45/MWh. Solar is expected to have a median cost of $44/MWh. For On-shore wind it will be $39/MWh, and for Off Shore Wind it is $36/MWh.

To put these numbers into perspective, if the average household electricity consumption kWh per day is 28.9 kWh (EIA, 2017 study) electricity from solar costs $1.27 per day, Onshore wind costs $1.13 per day, and Offshore wind costs $1.04 per day. Assuming a train needs 2,400 kWh energy to run for an entire day, the electricity from: solar would cost $105.60 per day, onshore wind costs $93.60 per day, and Offshore wind costs $86.40 per day, while gas-produced electricity would lag behind at a cost of $108.00 per day. This demonstrates how the price of renewables have gone down significantly and will no longer be a concern as long as there is infrastructure built to support electrification.

An alternative method to source hydrogen would be to store and transport it using Liquid Organic Hydrogen Carriers (LOHC's), which will incur a different set of costs. The current estimates for the cost of consuming Hydrogen through LOHC's is tabulated below:

LOHC Type	Cost of each LOHC per kg of H2	Cost for daily consumption of 50k kg of H2
Ammonia	$7.28	$364,000.00
Methanol	$6.52	$326,000.00
MCH	$6.27	$313,500.00
GH2	$4.80	$240,000.00

While these costs of LOHC's encompass the cost of H_2 production, LHC production, transmission, LHC decomposition, geological H_2terminal & storage, and distribution, the application of LOHC's would require even more funds to create and maintain LOHC's chemical manufacturing plants, the transport network infrastructure for LOHC specifically, and to support research to develop fuel cells that can leverage LOHC's since one can only obtain electricity from the LOHC's if one breaks the chemical bonds that are holding hydrogen in the LOHC's compounds. While LOHC's prove to be a good method of transporting hydrogen in room temperature, it will come at a large cost and may further complicate the process of using hydrogen as a fuel.

Cost Implications of Long term Hydrogen Storage & Sourcing

In addition to considering the costs of storage within substances such as LOHC's one also needs to factor in the cost of large scale hydrogen storage such as geological storage. From a Sandia National Laboratories study, researchers considered a variety of different geological storage options that each could serve different purposes. While the most economical storage option would be utilizing depleted Oil & Gas Reservoirs, other options such as Salt Caverns, have very low permeability and have proven to be the most efficient option for peak load cycling, which involves stabilizing the electric grid by distributing short-term stored hydrogen to cities during the peak hours of energy usage. The table below demonstrates the cost of implementing four geological storage options and the cost of utilizing pipelines to supply the hydrogen.

Geological Storage of H2	**Salt Cavern**	**Depleted Oil/Gas Reservoir**	**Hard Rock**	**Aquifer**
Cushion Gas Capital Cost ($)	$11,227,540	$21,492,278	$11,227,540	$21,492,278
Geologic Site Preparation Total Cavern Site Development ($)	$21,492,278	n/a	$48,720,000	n/a
Compressor Capital Costs ($)	$27,539,480	$18,359,654	$27,539,480	$18,359,654
Pipelines and Wells Capital Cost, Full Pipeline Costs ($/ton)	$4.39	$6.26	$4.39	$6.26
Total Capital Costs	**$63,254,547**	**$40,106,938**	**$89,644,020**	**$40,999,458**
Pipeline costs for delivering 50,000kg per day	$241.96	$345.02	$241.96	$345.02

From examining all options, one can see that maintaining a source of hydrogen fuel and creating some form of a network is an extremely costly endeavor. This process of storing and transporting hydrogen also becomes more complicated when considering the cost of supplying hydrogen to different cities. Through the study's analysis on Houston, Detroit, Pittsburgh, and Los Angeles residents, one can see that each city's energy consumption rates, availability of infrastructure for storage, and their proximity to the hydrogen storage site affect the cost of implementing a hydrogen network in their region. By simplifying the calculations, we assumed each city consumes 50,000 kg of H2 per day.

Cost of Transporting 50,000 kg Hydrogen in 1 day	**Houston**	**Detroit**	**Pittsburgh**	**Los Angeles**
Pipeline Transport Distance (km)	16	146	304	525
Full Pipeline Costs	$241.96	$3,752.26	$9,316.72	$18,343.54
Full H2 Wells Cost	$2,550.19	$13,594.24	$30,320.14	$2,550.19
H2 Transportation and Well Cost Total	**$2,792.15**	**$17,346.50**	**$39,636.31**	**$2,094.39**

Comparing Hydrogen to Alternative Sources of Energy

Green Diesel vs. Green Hydrogen

When conducting a cost analysis, it is also important to consider the cost of using alternative forms of energy such as green/renewable diesel, which is a fuel generated from processing waste agricultural feedstocks, oil derived from soybeans and corn and waste animal fats. Green diesel can be used by regular diesel engines and it has the capability of reducing emissions of diesel locomotives by up to 90%. According to partnered California-based green diesel companies called Valero and Diamond Green Diesel, their business operation costs for green diesel production will be $0.45 per gallon, and if these companies were to produce enough **renewable diesel** to meet the consumption of diesel by the US for an **entire day**, their **operations would cost $2,135,700**. From looking at the table below, one can see that the operation costs for a diesel company is significantly lower compared to operation costs for green hydrogen production using different electrolysis methods:

"Fuel" Production	**Year**	**PEM**	**SOE**	**AE**

Long-term expenses (CAPEX)	2020 (mid/high range in price improvement)	$1182/kW	$1346/kW	$1268/kW
Long-term expenses (CAPEX)	2025	$1065/kW	$1075/kW	$1065/kW
Long-term expenses (CAPEX)	2030	$737/kW	$737/kW	$865/kW
Daily operation expenses (OPEX)	2020, 2025, 2030	$10.786 mil /MW	$10.786 mil /MW	$10.786 mil /MW

The calculation of cost for the above table assumes that one hydrogen production facility has the daily energy capacity of 1MW and has a fixed daily operation cost of $40/kW of (energy from) H2 produced and it accounts for the projected cost of three types of fuel cells in the years 2020, 2025, and 2030.

While continuing the use of diesel locomotives is an option, green diesel still creates emissions, which can later have greater environmental and financial costs, as an application of a carbon tax on emissions could increase the price of regular and renewable diesel for consumers. Assuming the US consumes 3,049 gallons of diesel per day, and using Canada's carbon tax on fuel, this table shows the cost of diesel and green diesel.

Carbon tax for Year	Cost for 3,049 gallons	Diesel	Renewable Diesel
	Pre-carbon tax	$9,665.33	$11,220.32
2021	$0.4062/US gal	$1,238.50	$1,238.50
2022	$0.5076/ US gal	$1,547.67	$1,547.67
		Carbon Tax Growth rate/ yr	24.96%

Batteries vs. Green Hydrogen

The costs for a BEMU that requires a battery that can hold 2,400 kW worth of energy (daily) are:

Year	Batteries	Cost of train battery
2019	$156/kWh	$374,400.00
2023	$100/kWh	$240,000.00
2030	$61/kWh	$146,400.00

When comparing hydrogen to batteries, they both can be viewed as a means of energy storage that can provide electricity to power trains on-demand. However, because hydrogen production, sourcing, and application requires more processes, it is more complex than batteries, and this complexity reflects in the costs of using hydrogen powered trains (HEMU) as opposed to using battery powered trains (BEMU). Batteries are simpler than hydrogen and can be more readily deployed in current trains, which make it a more attractive option since a train with a **single hydrogen PEM fuel cell with a 2,400 kW capacity could cost $2,836,800**.

From only examining the costs of the necessary processes to obtain hydrogen and take advantage of the energy that it can store, one can see that without the instance of drastic changes in policy or funding, hydrogen cannot reach cost competitiveness with alternatives such as green diesel and batteries in the near term.

The Infrastructure for the Train - City/Regional/USA Scale Costs

Through our analysis, the best locations that could implement hydrogen technologies and applications (such as trains) are the Midwest, Mountain States, East and West Coast, in the US; more specifically, California, Texas, and Louisiana would serve as ideal locations due to the existence of hydrogen production facilities, and heavy concentration of space for three existing types of geological storage. Other ideal locations to place hydrogen production facilities and related technologies could be New York, Pennsylvania, etc. due to available geological storage and the emerging off-shore wind projects that could supply even more renewable energy to those regions (see diagram below).

While examining the financial requirements for implementing hydrogen train infrastructure, one can see that while the cost of obtaining hydrogen and implementing hydrogen train technology is the most costly option, the cost of implementing train infrastructure for HEMU's (Hydrogen-Electric Multiple Unit train) is the lowest out of all of the other train options, which yields an annual cost of ~**$14.3 million**. Assuming the average round trip distance a freight train travels to deliver goods is 183.24 km, these are the costs of maintaining and operating the infrastructure for the four different types of trains (DMU, EMU, BEMU, and HEMU):

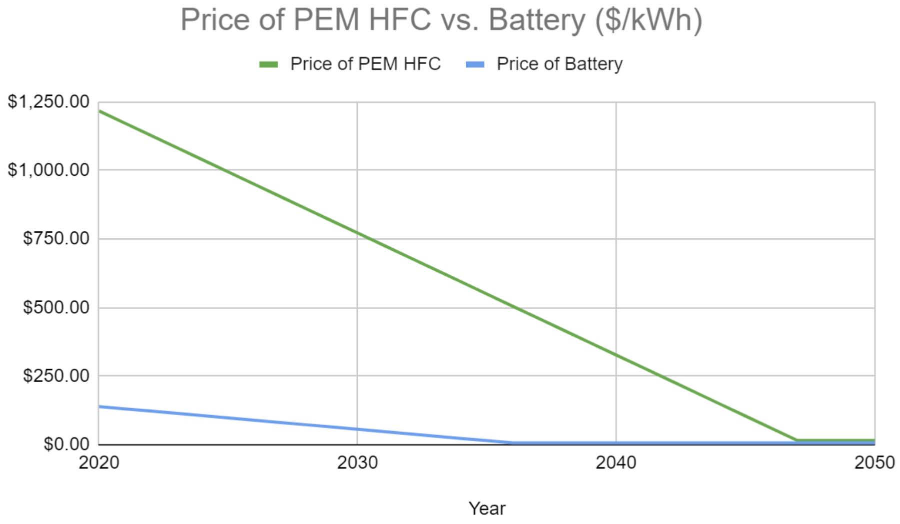
Type of Infrastructure & Cost	**DMU**	**EMU**	**BEMU**	**HEMU**
Train path (per yr)	$7,981,240	$7,981,240	$7,981,240	$7,981,240
Train Station (per yr)	$3,053,660	$3,053,660	$3,053,660	$3,053,660
Traction Energy (per yr)	$3,927,180	$1,688,480	$1,090,680	$1,945,900
Infrastructure Investment (per 30 yrs)	$427,000	$257,493,200	$6,100,000	$1,220,000
Infrastructure Operation (per yr)	$24,400	$305,000	$61,000	$36,600
Refuelling Journey (per yr)	$3,660	0	$0	$3,660
Recharging Dynamic Battery (per yr)	n/a	n/a	n/a	$57,340
Total Cost	**$15,417,140**	**$270,521,580**	**$18,286,580**	**$14,298,400**

The Rolling Stock and Components

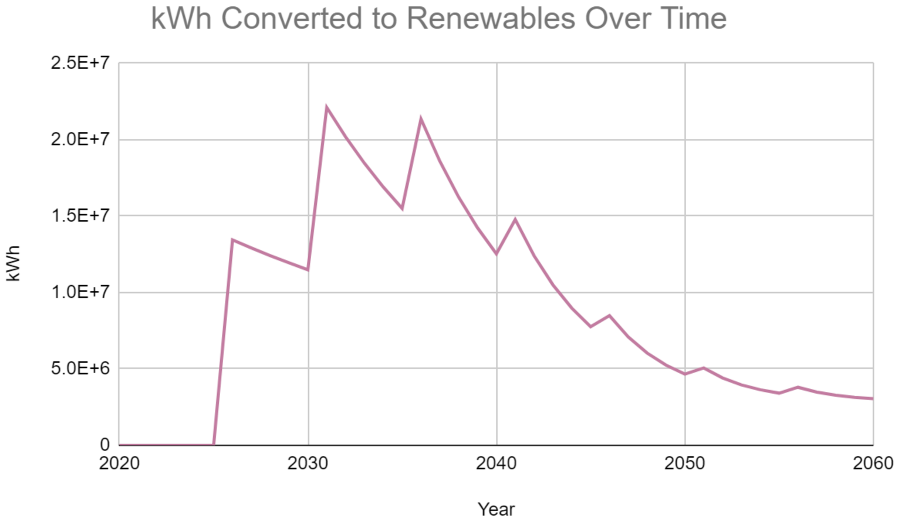
As the economics of freight railcar investment are complex and vary between companies, we will be setting assumptions from America's Class I rail industry. One of the biggest initial assumptions pertains to the largest and most substantial financial burden of railway industries when switching over to hydrogen powered trains: infrastructure costs. Assuming that out of the 3 categories governing railway cost structures (infrastructure network costs, train operating costs, and corporate overhead costs) the largest component of cost for rail industries will be the infrastructure costs of retrofitting, it's important to look at one basic component within privatized railroad companies: the rolling stock. This rolling stock refers to railway vehicles (powered and unpowered) such as railroad cars, locomotives (powered rail cars used to pull trains), coaches (passenger cars), wagons, and private railroad cars. These rolling stock components, when connected in series.

When it comes to the pricing of creating, and retrofitting rolling stock, the assumptions on the pricing of each component is utilized to determine the cost of a new hydrogen fuel cell (HFC) locomotive with a liquid-hydrogen refueled tender car attached. This is because, unlike Alstom's passenger HFC trains which work with completely redesigned coaches, it is more efficient to change the fewest amount of cars in the trains systems and not modify the already existing majority of freight cars (e.g. boxcars, etc.). Understanding we will only be replacing the assumptions we included in our analysis are as indicated at the top of the report.

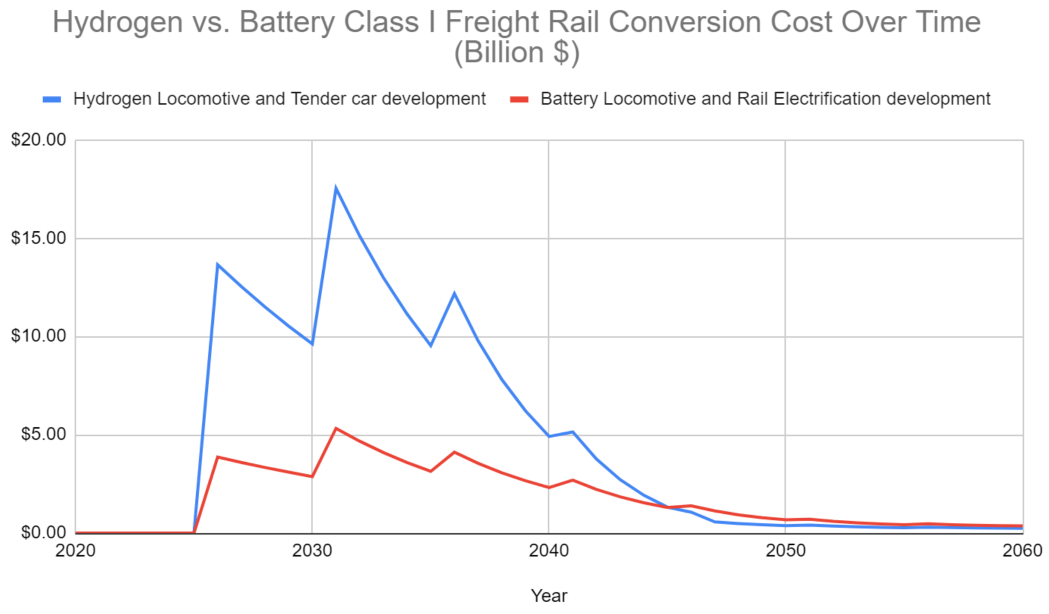
From our data gathered on the trends of locomotive growth, the conversation rate for aggressive governmental strategies, and trends of cost and efficiency over time; we were able to develop multiple projections of cost. The first most elementary component is the individual cost projections of the target technology which powers the train (see diagram below). Here, the last two assumptions are applied to the cost of each target technology over time, leaving batteries as the economically superior choice until the late 2040s.



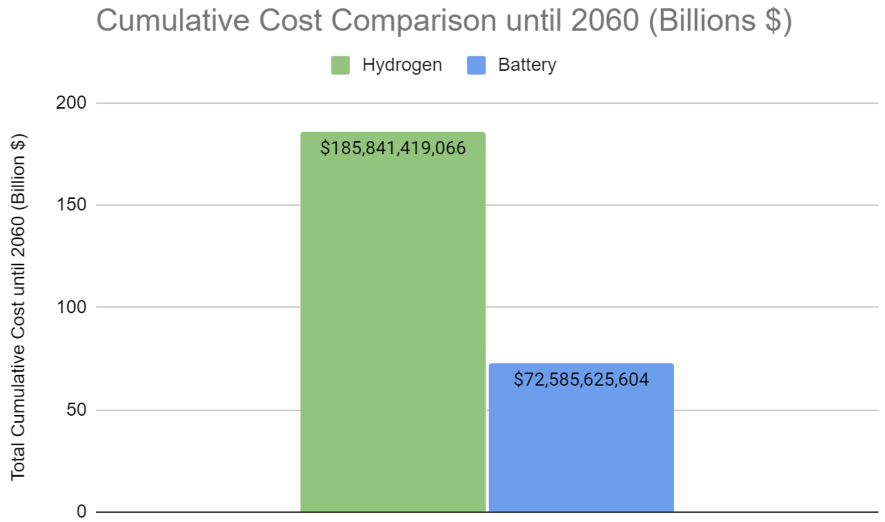
One of the most vital components of the entire analysis was determining the kWh projected to be needed by Class I Freight Trains over time (see diagram below). However, it must be noted that this number only includes the locomotives to be converted to a target renewable technology. This was determined by the projected number of locomotives to be converted to an additional 5% every 5 years after 2026 and assumptions of the average weight carried per train.



With these trends of rolling stock conversion, the infrastructural costs must be taken into account. In order to do this, aside from locomotive conversion, we assumed the next biggest expense would be either hydrogen storage in an additional "tender" car or the complete electrification of the railroads. Applying the assumptions of these costs and following the demand in conversion rate for the rolling stock, we were able to create a more holistic cost estimate over time than the previous graphs. More specifically, the prices of Class I freight rail conversion from diesel between hydrogen and electrification/battery were projected between 2020 and 2060 (see diagram below).



Our results show that the conversion to HFCs compared to battery/electrification is considerably higher over time until the mid-2040s. Additionally, the cumulative cost of hydrogen between 2020 and 2060 is approximately 2-3 times higher. This results in a HFC conversion being ~$185 billion and battery/electrification being $75 billion (see diagram below).



One can see that a switch to battery and electrification could prove the most beneficial

However, aside from this seemingly obvious answer, potential fault in these calculations lies within its simplicity of the market as we did not consider more complex or hidden costs, some of which were already touched upon, such as:

- Opportunity Cost to charge/refuel

- Opportunity Cost of unutilized tracks during electrification
- Lifetime of a train, battery, or HFC
- Efficiency over time
- Contributions of CCS as it aligns with Carbon Tax
- Pushback from private freight entities
- Transportation costs
- Safety risks

Biden's Infrastructure Plan

With a general understanding of the minimum financial support needed for freight trains to convert to renewables, is there enough governmental support and incentive to bridge the gap until the mid 1940s when electrification will cost more than HFCs?

The potential of governmental investment in the U.S. rail system is clearer than ever before as President Biden has announced a major priority to invest approximately $2 trillion into an infrastructure plan to modernize transportation. Among this, $80 billion is routed to the depreciated rail system to be distributed over the next 8 years. This number might seem like enough to bridge the gap between hydrogen for this short period of time, but would this support be enough to propel enough innovation to properly compete with electrification from this point onward?

Regardless, not only do we doubt that this much money will be pushed once it is tweaked in Congress, but the White House overview addressed mostly pushing "grant and loan programs that support passenger and freight rail safety, efficiency, and electrification." With hydrogen not in the picture and all-electric, high-speed rail dominating the passenger train market, there might be potential for more accelerated progress in the efficiency of electrified rail. Additionally, while green hydrogen is mentioned within political plans, little is said about specific investments on large-scale build out of electrolyzing technology throughout the US.

Conclusion

MODULE 1

Just as the growth and potential of hydrogen has changed the tune of many highly esteemed individuals with a deep knowledge of the energy industry, such as Nobel Laureate Dr. Steven Chu, so too will it change the tune of railway industry leaders. With enough supportive government policy centered around preparing hydrogen power technology initiatives to prepare it for a market takeover, the move to hydrogen is beneficial throughout the freight transportation sector in the U.S. and other worldwide use of energy. The application of HFC varies from continent to continent and should be looked at on a regional scale. Moving into module two, we could look at what locations are in the earlier stages, such as consideration and researching like Korea and the USA. By targeting countries and possibly cities at an earlier stage, we can start making arguments on why and how HFC trains should be implemented. We can explore the scale of implementation, locations, cost analysis, social implications, possible alternatives, what entities to work with, etc.

MODULE 2

Overall, hydrogen technologies are already being implemented due to their positive impact on the environment, local government, and current rail infrastructure. Through our research and suggestions, hydrogen trains' trends are rapidly occurring throughout the different types of economies and train rails. This is due to new wave climate-conscious consumer choices and net-zero governmental initiatives. Our overall solution is to push for more private and public investment, universities and institutional R&D, and campaigning the benefits of this type of infrastructure to the public. As the industry's growth continues, more investment will bring about a positive feedback loop, propelling hydrogen-powered trains into the future. As we move forward to module 3, we will investigate and strengthen our solution with a financial analysis of hydrogen trains.

MODULE 3

Hydrogen Trains are a more expensive option when analyzed on a surface level, and would require a larger amount of governmental support and R&D to compete with the pricing of batteries in order to become competitive.

Considering an aggressive cumulative HFC conversion until 2060 is ~$185 billion, while battery/electrification is ~$75 billion, there would need to be a significant amount of governmental support. However, there are no significant aggressive plans set forth for hydrogen train technologies as it is for batteries and electrification. Furthermore, the available technologies to fully leverage the energy storage from hydrogen is lacking, as most researchers are still trying to develop devices to solve issues related to hydrogen production, storage, and usage, and such devices have not reached the stage of developing manufacturable products, which have costs that can be quantified. These issues continue to leave hydrogen at a financial disadvantage compared to battery/electrification alternatives.

Aside from these explicit costs, there are a plethora of implicit environmental and public health costs (oil spills, fossil fuel emissions, asthma, sound pollution, etc.) that are also important to take into account when considering a more detailed cost analysis. As electrification is only as clean as the source, would it also provide the environmental benefit that drew it to the forefront to begin with? Regardless of our findings, this is still an important thought to consider.

MODULE 4

While initial research and planning seemed promising with the idea of hydrogen meant to be the most efficient freight technology, solutions cannot be created where there is no capital support for them. In this case, even though the practicality of hydrogen may fit into certain niches in other parts of the world (Europe, East Asia, etc.) or other industries entirely (manufacturing, maritime trade, etc.), their current pricing and projection within the American Class I Rail industry is not feasible in its current state. With little information on actualized and aggressive rollouts to support hydrogen related technologies, the prevalence of support sufficient enough to bridge the gap between HFCs and batteries/electrification is uncertain and economically too risky to rely on.