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Identification and Analysis of hydrogen value chains for transit buses and medium-heavy duty transport in Southeast Mexico

Tesis que presenta

Juan Antonio Herrera Contreras

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RECONOCIMIENTO

Por medio de la presente, hago constar que el trabajo de tesis de **Juan Antonio Herrera Contreras** titulado "**Identification and Analysis of hydrogen value chains for transit buses and medium-heavy duty transport in Southeast Mexico",** fue realizado en la Unidad de Energía Renovable, en la línea de investigación **Conversión, Almacenamiento y Gestión de Energía**, del Centro de Investigación Científica de Yucatán, A.C. bajo la dirección del **Dr. Luis Carlos Ordóñez López** perteneciente al Programa de Posgrado en Ciencias en Energía Renovable de este Centro, y la codirección del **Dr. Ulises Cano Castillo**, de SENER SRI.

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ACRONYMS

AFC Alkaline Fuel Cells.

API Administración Portuaria Integral.

BEV Battery Electric Vehicles.

CHIC Clean Hydrogen in European Cities.

DMFC Direct Methanol Fuel Cells.

EDS Electric Drive System.

EPA Environmental Protection Agency.

FCB Fuel Cell Bus.

FCEV Fuel Cell Electric Vehicles.

FCT Fuel Cell Truck.

FCT Fuel Cell Trucks.

GE General Electric.

GHG greenhouse gases.

GREET Greenhouse gases, Regulated Emissions, and Energy use in Transportation.

H2A Hydrogen Analysis Production Model.

HDRSAM Heavy-Duty Refueling Station Analysis Model.

HRS Hydrogen Refuelling Station.

IMCO Instituto Mexicano para la Competitividad.

IMU Índice de Movilidad Urbana.

IRR Internal Rate of Return.

JAPAY Junta de Agua Potable y Alcantarillado de Yucatán.
JIVE Joint Initiative for Hydrogen Vehicles Across Europe.

MCFC Molten Carbonate Fuel Cells.

NASA National Aeronautics and Space Administration.
NVP Net Present Value.

PAFC Phosphoric Acid Fuel Cells.
PEMFC Polymer Electrolyte Membrane Fuel Cells.
PIMUS Plan Integral de Movilidad Urbana Sustentable.

SEFOET Secretaría de Fomento Económico y Trabajo.
SITUR Sistema Integral de Transporte Urbano.
SMR Steam Methane Reforming.
SOFC Solid Oxide Fuel Cells.

USDOT U.S. Department of Transportation.

ZEV Zero Emission Vehicle.

RESUMEN

Este trabajo presenta una propuesta de cadena de valor sobre el uso de hidrógeno como combustible alternativo para el transporte público o de carga regional de combustibles de aviación en Mérida, Yucatán, México. Se propone que el hidrógeno se produzca por electrólisis utilizando fuentes de energía renovable y se utilice en vehículos eléctricos basados en celdas de combustible. Además, se realiza una comparación entre el hidrógeno verde, el hidrógeno gris de la red eléctrica y el diésel para evaluar los requisitos energéticos y las emisiones resultantes. Además, se realiza un análisis financiero entre las tres fuentes de combustible para comparar la viabilidad del proyecto en las condiciones actuales.

El requerimiento total de hidrógeno para el proyecto es de 1035 kg/día de H_2. Comparando las fuentes de combustible, el hidrógeno gris es el más enérgicamente intensivo debido a la composición de la red eléctrica, seguido del diésel y el hidrógeno verde utilizando plantas de energía fotovoltaica solar . El mismo patrón se aplica a las emisiones de gases de efecto invernadero, con la particularidad de que los vehículos de celdas de combustible son de emisión cero, las emisiones de GEI relacionadas con ellos están relacionadas en la forma en cómo produce el hidrógeno.

En las condiciones actuales, el hidrógeno gris costaría 11.44 USD/kg, el verde 7.55 USD/kg y el diésel en México cuesta 1.36 USD/L. Además, se consideran los subsidios gubernamentales al transporte público de 1,08 USD/km, tarifas de 0.83 USD/pasajero y el costo de transporte de Jet A1 es de 0.06 USD/km. De manera consistente, el diésel tuvo el mayor Valor Presente Neto tanto para el transporte público como de carga, 7,328,337.87 USD y 8,300,254.52 USD, respectivamente. El hidrógeno verde se acerca al proyecto diésel con el 86.7% y el 99.4% de sus valores, mientras que el VPN del hidrógeno gris está más alejado con el 49.5% y el 53.2% de los valores del diésel para el transporte público y de carga, respectivamente. Curiosamente, el transporte de carga impulsado con hidrógeno verde superaría los ingresos acumulados del transporte que consume diésel. El transporte con hidrógeno verde sería competitivo en las consideraciones actuales; las políticas de transporte y las regulaciones ambientales más estrictas podrían hacer más atractivo el proyecto.

ABSTRACT

This work presents a value chain proposal about using hydrogen as an alternative fuel for public transport and regional cargo for aviation fuels in Merida, Yucatan, Mexico. It is proposed that hydrogen would be produced by electrolysis using renewable energy sources and used by Fuel Cell based electric-vehicles. Furthermore, a comparison between green hydrogen, gray hydrogen from Mexico's National Grid, and diesel, is made to evaluate the energy requirement and emissions from each fuel source. Additionally, a financial analysis of the three fuel sources is made to compare the project feasibility under current conditions.

The total hydrogen requirement for the project is 1035 H2kg/day. From the hydrogen production comparison by source, gray hydrogen is the most energy-intensive because of Mexico's national grid composition, followed by diesel and green hydrogen from electrolysis and using solar photovoltaic power plants within the region. The same pattern applies to greenhouse gas emissions with the particularity that fuel cell vehicles are Zero-emission vehicles. The related GHG emissions are in connection to how hydrogen is produced.

Under current conditions, grey hydrogen would cost 11.44 USD/kg, green hydrogen 7.55 USD/kg, and diesel, in Mexico, cost 1.36 USD/L. Furthermore, governmental subsidies to public transport are considered to be 1.08 USD/km, fares are 0.83 USD/passenger, and the transportation cost of Jet A1 fuel is 0.06 USD/km. Diesel had the highest Net Present Value for public and cargo transport, 7,328,337.87 USD and 8,300,254.52 USD, respectively. Green hydrogen is close to the diesel project with 86.7% and 99.4% of diesel's values, while grey hydrogen NPV index is further from them with 49.5% and 53.2% of diesel's values for public and cargo transport, respectively. Interestingly, green hydrogen-fueled cargo transportation would surpass cumulative diesel revenue. Green hydrogen transportation would be competitive under current considerations; policies for better transportation and stricter environmental regulations could improve the project's attractiveness.

INTRODUCTION

Fossil fuels have fueled humanity's progress since the industrial revolution. At the beginning of fast industrialization in the Western world, there was no effort to reduce environmental impact as it was not a concern. However, as the population grew and the effects of industrial waste and pollution became notable, scientists in different countries started investigating the adverse effects of industries on the surroundings. Macro-scale environmental impacts were adopted for monitoring climate change, now accepted as the result of years of unimpeded industrialization and pollution. To combat the adverse effects of fossil fuels, the search for alternatives began as environmental concerns grew. While hydropower was previously the primary alternative for electricity generation, the cost reduction for photovoltaics and wind power installations has made them an attractive alternative for renewable electricity generation. However, all renewable energy sources have different drawbacks, such as intermittence, which is the biggest one to overcome. Energy storage solutions such as pump hydropower, massive battery storage, molten salt, flow batteries, compressed air, and flywheels have been proposed, but only hydrogen is considered a substitute for oil as the primary energy vector for society.

Hydrogen can be used for energy storage or directly as a fuel, similar to natural gas, or to provide electricity through electrochemical reactions in fuel cells. Hydrogen is obtained by steam reforming of natural gas or by electrolysis. The second case means that when renewable generation is high, and demand is low, the excess electricity can be used for hydrogen production, stored, and then used to provide the energy demand when needed. For transportation, fuel cell technology is proposed to replace the internal combustion engine as vehicles' internal primary energy source. This transportation evolution is being tested worldwide, with hydrogen distribution and service stations being constructed to encourage citizens to change their current vehicles for hydrogen-powered new units. Different city governments and regional authorities are adopting this technology and proposing hydrogen fuel cell-powered buses as public transportation, tackling issues like environmental impact and urban mobility within their borders. In Mexico, the market penetration of alternative technologies for mobility has been slowly rising while cities are getting bigger. The accelerated urban development has impacted how cities are planned, as much of the infrastructure has been built with the expectation of rising private automotive vehicle usage. In cities such as Guadalajara, Monterrey, and Mexico City, where there are currently many public transport options, their infrastructure is lacking compared to road and highway development.

This trend shows disparities between cities and regions. Of the country's top 20 most significant cities, 18 are either in Northern or Central Mexico (INEGI 2021b), while fewer cities surpass 100,000 residents in the Southwest, according to the 2020 National Census. In that list, Mérida, Yucatán, is the 12th by population, with 921,771 residents (INEGI 2021a), the biggest in the region, more extensive than other capital cities in the country like Saltillo and Hermosillo, just ahead of Cancun, the major tourist destination in Quintana Roo. Mérida is also well positioned between Central Mexico and the Mexican Caribbean and Mayan Riviera; with the port of Progreso north of it, the city has evolved into the region's commercial, educational, technological, cultural, and financial hub.

This work aims to describe a public transport route serviced by a fleet of fuel cell buses, as well as the infrastructure and the hydrogen and energy requirements for this route within Mérida and another one for a Progreso-Mérida cargo route.

CHAPTER 1

BACKGROUND

A transport project that aims the introduction of alternatives, such as hydrogen, to conventional mobility has to cover different critical aspects including research into hydrogen properties, its production, storage, and handling, as well as the Fuel Cell Bus (FCB) and Fuel Cell Truck (FCT) market. The integration of related infrastructure must be conducted to propose an actual supplier of the technology and the design of the refueling stations. Furthermore, a deep look into transportation infrastructure in and around Merida is required for cargo and urban transport route planning. Each project requires different information-gathering approaches, as the objectives are different.

1.1 Hydrogen

Hydrogen is the most abundant element in the universe, comprising about 75% of its mass. On Earth's crust, however, it is present in small quantities, representing less than 0.15% of its composition by weight (Jolly 2022). The element can be found in various forms, including water, bonded with carbon in hydrocarbons, and hydrides, here the hydrogen in its anionic form bonds with a more electropositive element.

Traditionally, hydrogen has been handled in either a gaseous or liquid state for production and storage. However, recent advancements in solid-state storage technology have been made to address the limitations of these methods.

In addition to these traditional methods, such as steam reformation of natural gas, there are several cleaner alternatives for hydrogen production. For instance, using renewable energy to power the electrolysis process can efficiently produce hydrogen. Figure 1.1 shows a schematic of the hydrogen production process. Other novel production methods include photochemical splitting and biological production. These methods have the potential to be more sustainable and environmentally friendly.

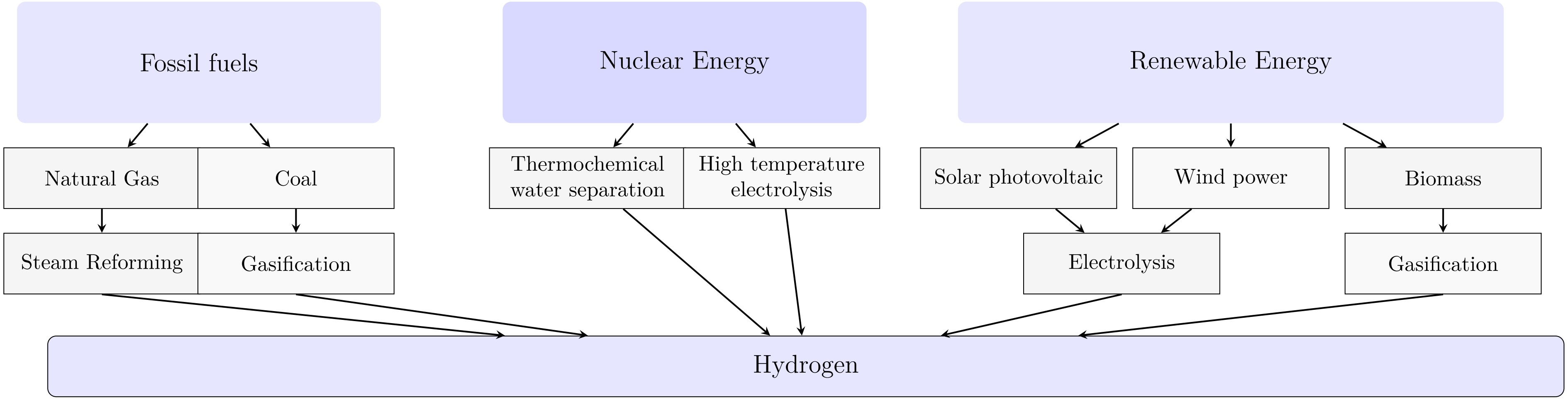


Figure 1.1: Hydrogen production methods (Acar and Dincer 2014)

Depending on the method of production, hydrogen can be classified into different categories based on its color. The three main types of hydrogen are gray, blue, and green. Gray hydrogen is predominantly produced through the Steam Methane Reforming (SMR) process, which utilizes natural gas. This method accounts for approximately 96% of global hydrogen production. However, it is important to note that gray hydrogen production results in significant CO2 emissions.

To address the carbon emissions associated with hydrogen production, blue hydrogen has been introduced. Blue hydrogen follows the same SMR process as gray hydrogen but incorporates a carbon capture and storage (CCS) system to reduce or eliminate CO_2 emissions. By capturing and storing the CO_2 produced during hydrogen production, blue hydrogen aims to mitigate its environmental impact and transition towards a more sustainable energy source.

On the other hand, green hydrogen is produced using renewable energy sources and does not generate any greenhouse gases (GHG) emissions. Various methods exist for green hydrogen production, but electrolysis has emerged as a leading choice. Electrolysis involves the separation of water molecules using electricity derived from renewable sources like solar and wind power. This process allows for the production of hydrogen without any associated carbon emissions, making it a highly sustainable and environmentally friendly option.

Hydrogen is a versatile gas used in various industries, including food, metallurgy, cosmetics, pharmaceuticals, and oil refining. Due to its clean-burning properties, there has been growing interest in using hydrogen as an alternative fuel. Hydrogen produces only water vapor and heat when it reacts with oxygen in a fuel cell, making it a promising candidate for reducing greenhouse gas emissions and combating climate change.

While hydrogen offers many potential benefits as a fuel, its handling and storage present unique challenges. Gaseous hydrogen has a low density and can easily escape confinement, making storing and transporting it safely difficult. Additionally, hydrogen can diffuse into the material of storage vessels, causing them to become brittle and prone to cracking. To ensure the safe handling of hydrogen, specialized storage, and transportation equipment is required, as well as strict safety protocols and detection systems capable of accurately measuring the gas to prevent buildup and explosions.

Despite these challenges, hydrogen remains an attractive alternative fuel option due to its abundance, versatility, and potential to reduce greenhouse gas emissions. As research continues to explore new and innovative ways to produce, store, and utilize hydrogen, it is expected to play an increasingly important role in our transition to a more sustainable energy future.

1.2 Fuel cells

Studies into fuel cells materialized in the early 1800s by Sir William Grove, who demonstrated an experimental process based on his experience with electrolyzers, combining hydrogen and oxygen to produce electricity. Further investigation by Francis Bacon yielded a fully operational fuel cell. As part of the space program by NASA, the technology was extensively used in the 60s, using pure oxygen and hydrogen (Sharaf and Orhan 2014).

Fuel cells convert the chemical energy stored in a fuel directly into electricity through electrochemical reactions. They operate like a battery, but unlike batteries, they do not require recharging and will continue to produce electricity as long as the fuel is supplied. Fuel cells can use a variety of fuels, including hydrogen, natural gas, methanol, ethanol, and even gasoline. However, the most common and cleanest fuel for fuel cells is hydrogen, as it produces only water and heat as byproducts.

This devices are comprised of two electrodes, the negative pole is the anode, while the cathode is positive charge, separated by an electrolyte. The fuel is supplied to the anode, while oxygen or air is supplied to the cathode. The fuel then is oxidized, producing electrons and positively charged ions. The electrons flow through an external circuit, generating electrical power, and the positively charged ions flow through the electrolyte to the cathode. At the cathode, the oxygen or air combines with the electrons and the positively charged ions to produce water and heat.

Fuel cells have many advantages over traditional combustion engines, including higher efficiency, lower emissions, and quieter operation. They can be used in various applications, including transportation, stationary power generation, and portable power. However, fuel cell systems have challenges, such as the high cost of materials, the need for hydrogen storage and distribution infrastructure, and the technical complexity of fuel cell systems (Scott 2011).

Table 1.1: Types of Fuel Cells

Types of Fuel Cells		
Fuel Cell Type	**Description**	**Advantages**
Direct Methanol Fuel Cells (DMFC)	It uses liquid methanol as fuel. It is oxidized to carbon dioxide while oxygen is reduced to water. Higher energy density compared to electrochemical batteries and quick refueling times.	High energy density, quick refueling times.
Alkaline Fuel Cells (AFC)	They were the first working cells capable of delivering significant power, used primarily in transportation. Recently developments of Anion Exchange Membranes have led to a resurgence in AFC development.	New AFC devices due to new anion exchange membranes.
Phosphoric Acid Fuel Cells (PAFC)	Designed for terrestrial use, it uses phosphoric acid as an electrolyte. Carbon monoxide tolerance and the capability to work with higher concentrations of carbon dioxide in the fuel used.	Tolerance of carbon monoxide, high concentrations of carbon dioxide in fuel, ability to use reformed organic fuels.
Molten Carbonate Fuel Cells (MCFC)	High-temperature cells are often used for stationary power generation. The operation temperature is between 600 and 650°C, capable of processing natural gas into hydrogen used in fuel cell reactions.	No noble metals catalysts or ceramics and specialized alloys for heat resistance required, heat can be used for the reformation of the fuel.
Solid Oxide Fuel Cells (SOFC)	Suitable for sectors requiring over 50 MW of power, such as portable and stationary power generation, up to utility-scale size. Fuel flexibility, with unused fuel expelled and burned in tailpipe steam, gases are reused in the reformation stage of the process	The flexibility of fuel, high power output capability, and gases reused in the reformation stage of the process

Sources:Bidault and Middleton 2012; Braun et al. 2012; Kamarudin et al. 2009; Leo 2012; Sudhakar et al. 2018

1.2.1 Polymer Electrolyte Membrane Fuel Cells (PEMFC)

Proton Exchange Membrane Fuel Cells (PEMFC) generate electricity through hydrogen oxidation and oxygen reduction electrochemical reactions. PEMFCs use a polymer electrolyte membrane, which facilitates the transport of protons across the cell, separating fuel and oxidant while forcing the passage of electrons through an external circuit. The reaction occurs at the electrode's surface, where hydrogen is oxidized, while oxygen is reduced to form water. PEMFCs are considered promising technology for various applications, including portable devices, transportation, and stationary power generation. They have several advantages over conventional fossil fuel-based power systems, including low emissions, high efficiency, and quiet operation (Shukla and Jackson 2013).

The development of PEMFCs dates back to the 1960s, and since then, extensive research has been conducted to improve their performance, durability, and cost-effectiveness. One significant challenge in commercializing PEMFCs is the cost of materials, especially platinum-based catalysts, which are required to facilitate the electrochemical reactions at the electrodes. Researchers are actively exploring alternatives to platinum-based catalysts, including non-precious metal catalysts and nanostructured materials. In addition, efforts are being made to develop cost-effective manufacturing processes and improve the membrane's durability (Y. Zhang et al. 2019). However, it was not until the 1980s that significant progress was made when General Electric (GE)) developed a practical PEM fuel cell system for NASA's space program. Since then, there has been extensive research on the materials and design of PEM fuel cells, leading to efficiency, durability, and cost-effectiveness improvements. PEM fuel cells have applications in various fields, including transportation, stationary power generation, and portable electronics (Baker et al. 2020).

In particular, several companies and research institutions are working on developing PEM-FCs. The automotive industry has shown significant interest in this technology, with companies such as Toyota, Honda, and Hyundai investing heavily in the development of fuel-cell vehicles. PEMFCs are also being used in stationary power generation systems, such as backup power for buildings and telecom towers, and in portable devices, such as laptops and cell phones. Research is ongoing to improve the efficiency and reduce the cost of PEMFCs to enable their widespread adoption in various applications (Schmidt 2019).

Overall, PEMFCs have shown great promise as a clean and efficient alternative to conventional power systems. Continued research and development are needed to improve their performance, durability, and cost-effectiveness to enable their widespread adoption in various applications.

1.3 Fuel Cell Buses

Diesel technology has long been the predominant power source in heavy-duty vehicle and bus industry. However, with increasing environmental regulations, especially in the EU, manufacturers

have been forced to improve engine efficiency and reduce emissions. This has resulted in the emergence of innovative alternatives, such as electric and fuel-cell vehicles, in the bus market. While both technologies have challenges, they present promising opportunities for reducing emissions.

Fuel-cell technology has several options, including alkaline fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, and solid oxide fuel cells. The automotive sector has mostly adopted Proton-exchange Membrane (PEM) fuel cells due to their simple design, quiet operation, and lack of toxic emissions. PEM fuel cells possess a high energy density and can handle stop-start conditions, making them a practical option for transportation (Alaswad et al. 2021; Lü et al. 2018).

As the transportation industry strives to curb emissions, there has been a surge in alternative options to diesel-powered heavy vehicles. Fuel cell-powered buses are one such alternative and offer many advantages over their fossil fuel-powered counterparts. These benefits include increased fuel ef- efficiency, zero tailpipe emissions, reduced noise pollution, and a significant reduction in greenhouse gas emissions on a well-to-wheel basis (Hua et al. 2014).

(a) VanHool Midibus Hybrid (b) VanHool Standard 12m bus Hybrid

(c) VanHool Articulated bus Hybrid (d) Wrightbus Fuel Cell Double decker

Figure 1.2: Example of different types of buses

The design of buses can vary greatly depending on customers' needs, which are often cities and government institutions. Service providers may require specific product specifications, such as passenger seating configuration, disability access options, indicators, screens, and other complementary features. Buses can also be classified based on their body structure, including single-deck or double-deck, rigid or articulated, and high-floor or low-floor models. Figure 1.2 provides examples of different types of buses worldwide.

1.3.1 Fuel Cell Bus adoption around the world

Several countries are pushing forward Fuel Cell Electric Vehicles technology; between 2018 and 2019, governments worldwide pledged to increase hydrogen infrastructure, including electric mobility, power, and supply chains. Specifically, in transport, the USA is still the largest market for FCEVs, but in recent years, Asian markets such as China, South Korea, and Japan have been constantly growing. China's role in this trend is not only for privately owned cars; the government has taken the policy of adoption and promotion of Fuel Cell Bus (FCB) and light-duty trucks, with 4300 and 1800 units respectively, becoming the leader in the global stock of this vehicles (IEA 2020).

China is not the only government supporting policies and initiatives in the field of hydrogen-based transport; Japan, under its G20 presidency, requested to IEA a report about the hydrogen future (IEA 2019). This report details the current state of hydrogen in different roles and their perspective. For transport, in 2019, Japan had 500 buses and 400 trucks powered by fuel cell technology; they argued that long-haul and heavy-duty applications were attractive options for hydrogen use. The Japanese market has the fastest growing, with a strong focus on national manufacture; the government's objective is to have 800,000 FCEVs and 1200 FCBs on the road by 2030 (Asif and Schmit 2021).

A robust distribution and refueling network for fuel hydrogen-powered vehicles should be developed. Similar problems to the adoption of Battery Electric Vehicless, one of the main drawbacks is the lack of recharging infrastructure, as well as many manufacturers started selling their vehicles with different connector types, and some regulations from the government resulted in companies being required to provide a connector adapter helping the adoption of this technology and the development of charging stations.

At the front of hydrogen distribution and refueling stations, Japan, Germany, and the US are the leaders in installations. The development of such a refueling network has been slow; In China, a refueling station can be built in six months; in other places, it takes close to two years (IEA 2019), partly due to these stations' low and variable utilization. Governments worldwide have chosen several policies to develop hydrogen-fueled vehicles and their adoption.

1.3.1.1 Europe

Europe has developed robust international interdependent economies, and the European Union's financial support might be given through many programs. With the necessity to change transportation technology, many programs have risen. In 2010, the Clean Hydrogen in European Cities (CHIC) project was a flagship zero-emission bus project, meaning electric and hydrogen buses, including infrastructure. In total, between 2010 and 2016, 54 fuel cell buses were demonstrated to be capable of being a solution to decarbonize public transport fleets across Europe (Fuelcellbuses.eu 2020). Several programs and projects came after CHIC; High V.LO-City; HyTransit; NewBusFuel; 3 Emotion; MERLIN and JIVE 1 and 2 are examples of such programs abording bus adoption, test runs, and hydrogen recharge infrastructure across Europe, the UK, and even Canada.

1.3.1.2 America

In the US, hydrogen bus technology has been slow, as most Zero-emission Buses are based on Battery technology rather than hydrogen. Only 3.1% of the total are fuel cell-based buses. Several federal or state-level proposals have been considered across the US to accelerate the adoption of this kind of FC-based vehicles. In 2015, the federal government and industry representatives reached a cooperation agreement called the National Fuel Cell Bus Program, trying to advance the commercialization of such technologies, providing combined funding of over $120 million in selected projects (Federal Transit Administration 2020).

In 2018, the California state government updated its Zero Emission Vehicleprogram to set the goal of 5 million ZEVs by 2030. That same year, several states signed a Memorandum of Understanding, pushing for collaborative strategies to transform the transportation sector (California Air Resources Board 2020). Their state effort promotes battery and hydrogen-powered buses and recharge-refuel infrastructure across California and other states.

More recently, in 2021, U.S. Department of Transportation (USDOT) announced $182 million in grants to 49 projects tackling low or zero-emission buses and related infrastructure as part of the Low or No-Emission Grant program (Federal Transit Administration 2021). Additionally, a bill has been proposed in the country’s senate; this so-called Clean Transit for America Plan, should it pass as is, would provide $73 Billion for zero-emission bus projects (Manthey 2021), This latter would be included in the broader CLEAN Future Act, which objective is an emission-free economy by 2050 (Randall 2021).

1.3.1.3 Japan

As stated before, the Japanese government has set ambitious goals for its hydrogen-based economy; one of the pillars is the transport sector. Japan´s unique situation, where the lack of energy resources such as oil and gas makes the nation dependent on imports, making up 94% of its primary energy supply, has pushed the government to take this approach.

In the early 2020s, the goal is to have 1200 hydrogen buses on the road and to lower the cost of the technology to 400,000 USD. Furthermore, the plan is to install 900 Hydrogen Refuelling

Station (HRS) to service the goal of 800k FCVs on the road. Other significant commitments are the electrification of ships using FC technology, the reduction of FCV cost to 5000 USD per kW, and hydrogen storage to 2,300 USD, to reduce of the price difference between FCVs and HVs to 5000 USD, and to reduce of the price of electrolyzers to 370 USD per kW, among others, while making the distinct choice of using carbon-free hydrogen, rather than Green hydrogen (Ministry of Economy, Trade and Industry 2019).

1.3.1.4 China

Despite China's government not defining a clear national strategy for hydrogen adoption, labeling it as a frontier area, the advancements in hydrogen adoption have been impulsed by different provinces. The national government has taken the approach of supporting these provincial and city administrations. Five clusters have surged and received support, the Beijing-Tianjin-Hebei cluster, Guang-dong, Henan provinces, and Shanghai. Up to 300,000 million USD in fiscal bonuses were awarded to local governments that comply with specific targets set by national authorities (Nikkei Asia 2021).

Hydrogen and electric vehicle development and adoption have been a constant, appearing in some way or form in the last several five-year plans, resulting in several advances in the sector. Several Chinese automakers have produced hundreds of FCEVs, making use of the power system platform on models such as the SAIC's Shanghai, VW's Passat and FAW's Besturn, among others. Moreover, this development has extended to the Fuel Cell Bus market. With China acting as a host for events such as the Olympics in 2008, demonstration projects were approved for such occasions, making them fully-fledged projects for the cities they served. Nevertheless, there are key areas to develop further that the nation has identified, such as FC durability for nationally developed stacks, access to some crucial materials and components, and onboard hydrogen storage, standing out as areas of opportunity (Strategy Advisory Committee of the Technology Roadmap for Energy Saving and New Energy Vehicles 2019).

Short-term goals for FCEVs included adopting 1500 Fuel Cell Buses, an increment from 174 in Hebei Province. It is expected that passenger cars will overtake the numbers of FC Buses and trucks by 2025, planned to be close to 40,000 on the road, totaling over 1 million units overall around 2030.

Alongside the number of vehicles, in 2030, there will be be over 300 Hydrogen Refuelling Station (HRS), and by 2050 over 1000 (Seißler 2019).

1.4 Fuel Cell Trucks

Fuel Cell Trucks (FCT), also known as hydrogen fuel cell electric trucks, are a promising application of fuel cell technology in the transportation sector. These trucks use fuel cells to generate electricity onboard, which powers the electric motor to drive the vehicle. They offer several advantages over conventional diesel trucks, such as zero-emissions, quieter operation, and improved efficiency (Carriquiry and Cunha 2020). In addition, FCT have a more extended driving range than battery-electric trucks, making them suitable for long-haul transportation (Davidson and Thring 2019).

Several companies are working on the development of fuel cell trucks. In 2019, Hyundai released the XCIENT Fuel Cell, the world's first mass-produced fuel cell heavy-duty truck with a driving range of 400 km on a single charge (Hyundai 2022). Toyota has also been testing prototype, the Project Portal, with a driving range of over 300 miles (Toyota 2022).Other companies, such as Nikola Corporation and Daimler AG, have also announced plans to develop fuel cell trucks for commercial use (Nikola Corporation 2022, Daimler AG 2022).

However, the deployment of FCT still faces several challenges. One significant challenge is the lack of hydrogen refueling infrastructure, necessary to support the operation of fuel cell vehicles. Developing a hydrogen infrastructure network requires significant investment and coordination among stakeholders, including government, energy companies, and truck manufacturers (Davidson and Thring 2019). In addition, the high cost of fuel cell systems compared to conventional diesel engines is another challenge that must be addressed to enable the widespread adoption of fuel cell trucks in the transportation sector (Carriquiry and Cunha 2020).

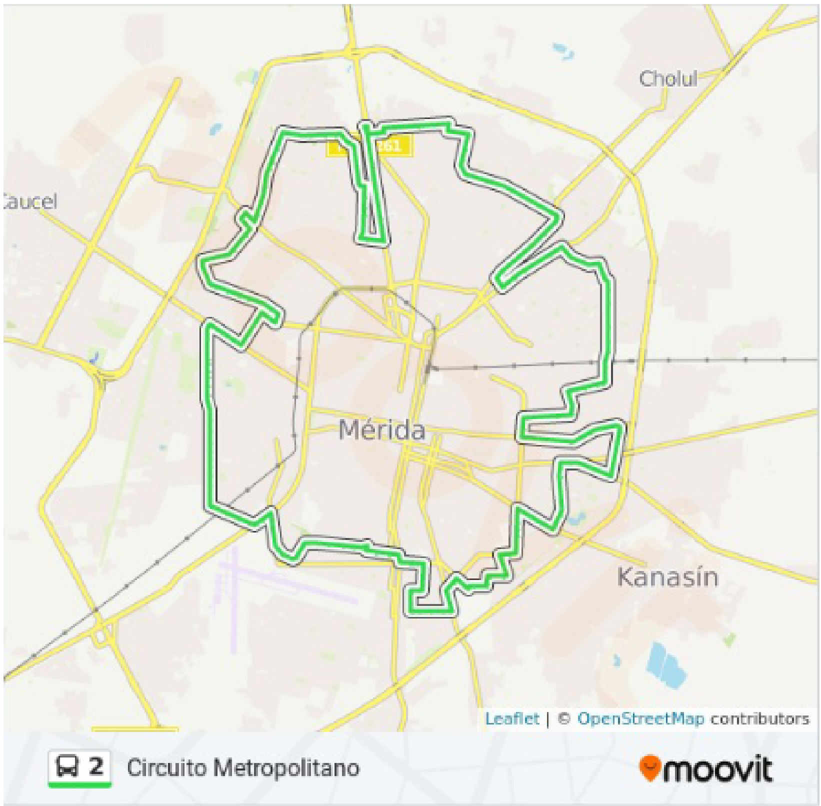
Despite these challenges, FCT hold great promise as a clean alternative to conventional trucks. Continued research and development are needed to improve performance, reduce costs, and support deploying a hydrogen infrastructure to enable widespread adoption in the transportation sector.

1.5 Transportation in Merida Yucatan

1.5.1 Urban routes

There are several routes in the city; according to the Moovit app, an app that specializes in tracking public transport to provide information to the population, there are 244 routes across Merida, Yucatan (Moovit app 2021), taking into consideration buses and “combis”, a kind of smaller van servicing a route. Despite having a plenitude of routes, the Index of Urban Mobility (Índice de Movilidad Urbana (IMU)) made by the Mexican Institute for Competitiveness (Instituto Mexicano para la Competitividad (IMCO)) ranks Merida 6th overall. This index evaluates different attributes of relevance, which are “Regulations and public policy in favor of mobility” and ”Urban Context,” where the city scores Mid-low and low, respectively, together; this index describes a lack of policy integration between urban development and transport infrastructure, resulting in consequences to the public, such as higher spending for transportation per user (Instituto Mexicano para la Competitividad 2019). Another document of importance is the Integral Plan for Sustainable Urban Mobility 2040 (PIMUS); it indicates that public transport handles 47% of the trips made by the inhabitants, while at the same time, the system has been slow to adapt to new necessities of the population, it presents low integration to other methods of transportation and low interconnectivity. Another problem for public transport use is that 80% of the routes arrive downtown, meaning that 60% of travel requires at least two buses to complete (Instituto Municipal de Planeacion 2019). Attempts to modernize urban transport have not been entirely successful.

Two critical routes serve Merida in a ring or circuit configuration; this allows users to cross the city, avoiding the downtown and using only one bus. The metropolitan circuit has been in service for some years now, the inner city circuit, while the newer, the peripheral circuit, serves as a connection between settlements far from the downtown.



(a) Route of the Metropolitan Circuit

(b) Route of the Peripheral Circuit

Figure 1.3: Examples of urban routes

1.5.1.1 Metropolitan Circuit

One of the most important routes that do not arrive at the historic downtown is the Metropolitan Circuit route (Circuito Metropolitano); it encompasses 223 stops along the route. The entire trip takes 160 minutes.

At the proposal stage of this circuit, it was planned to be a connection service for other routes that cross their path. As mentioned, many Merida routes start and finish downtown, causing users to use multiple buses and travel longer. The objective of the metropolitan circuit route was to allow transfers before arriving downtown and reduce traffic jams due to constant bus stops, and shorten travel time. In the beginning, the concession for managing the route was given to 5 transport companies, providing different buses, in 2019 the service was rebranded to be part of Sistema Integral de Transporte Urbano (SITUR), an attempt to rework the transport infrastructure in the city.

1.5.1.2 Peripheral circuit

The peripheral circuit, is part of the new governmental push towards a better transport system, the Metropolitan System of Sustainable Mobility, ”Va y Ven”. It connects 104 routes that traverse the peripheral ring, a mayor infrastructure that engulfs the city, coming from downtown to other settlements outside Merida; its objective is to quicken travel from the city outside and to prevent further travel towards the crowded city center.

1.5.2 Cargo routes

Merida finds itself in a unique position as the most important destination for products to sustain the increasing population of its metropolitan area and the state of Yucatan. The port of Progreso is just 36 kilometers north of Merida and is one of the biggest and busiest Mexican ports in the Gulf/Caribbean zone, according to Administración Portuaria Integral (API). TThe Mexican legal framework stipulates two classifications for ports, ”de altura,” or ports with international capabilities, and ” Cabotaje,” or ports only handling national transportation of goods. Progreso is an international port that handles cargo vessels and cruisers. It is the only port with such characteristics in Yucatán, and alongside Puerto Morelos in Quintana Roo, are the only ports in the Yucatan Peninsula mainland that are considered international.

Table 1.2 (Secretaría de Comunicaciones y Transporte 2021) shows the movement of international freight through ports in the Gulf-Caribbean region. It shows the importance of Progreso, as it handles various imports and exports. The different imports suggest that various industries and consumers use the port to supply their needs.

Table 1.2: International Freight movement, ports in the Gulf-Caribbean region 2021, Secretaría de Comunicaciones y Transporte 2021

Freight January-December (tons)							
Port	Uncontained	Containers	Agricultural	Mineral	Petroleum and derivates	Other fluids	Total
Altamira, Tamps.	2,479,260	6,794,852	784,668	4,925,093	-	3,286,550	17,725,092
Tampico, Tamps.	1,368,754	108,392	71,276	1,161,546	3,881,096	15,892	6,606,956
Tuxpan, Ver.	392,401	172,188	1,439,995	427,260	8,231,191	2,069,960	12,732,995
Veracruz, Ver.	2,526,259	9,676,554	6,943,665	2,852,640	1,789,980	1,852,213	25,641,311
Coatzacoalcos, Ver.	474,630	137,662	1,166,344	1,120,326	21,051,028	1,982,672	25,932,662
Dos Bocas, Tab.	14,031	-	73,100	-	25,353,334	13,569	25,454,034
Cayo Arcas, Camp.	-	-	-	-	20,604,044	-	20,604,044
Progreso, Yuc.	135,893	725,660	2,402,840	110,475	554,989	23,781	3,953,638
Puerto Morelos Q.Roo	1,751	21,987	-	-	-	-	23,738
Punta Venado, Q.Roo	-	-	-	8,111,064	-	-	8,111,064

1.5.2.1 Fuels transportation and distribution

One of the most important roles for Progreso and Merida is fuel storage and transportation to other cities in the Yucatan and Quintana Roo. The only fuel storage and distribution installations in Yucatán are located in this city (PEMEX Logística 2020). There is a facility close to Progreso and another within Merida; ducts connect both. Takers deliver the fuel from Madero and Pajaritos maritime terminals to Progreso. Then, it is transported by ducts to the storage facilities outside the Progreso port and then transported to Merida by ducts to be distributed in the city. The combined storage capacity for PEMEX's infrastructure is 313 million barrels of different products. In addition to PEMEX, there is a private storage facility in Progreso, with a capacity of 423.4 million barrels (Secretaría de Energía 2018).

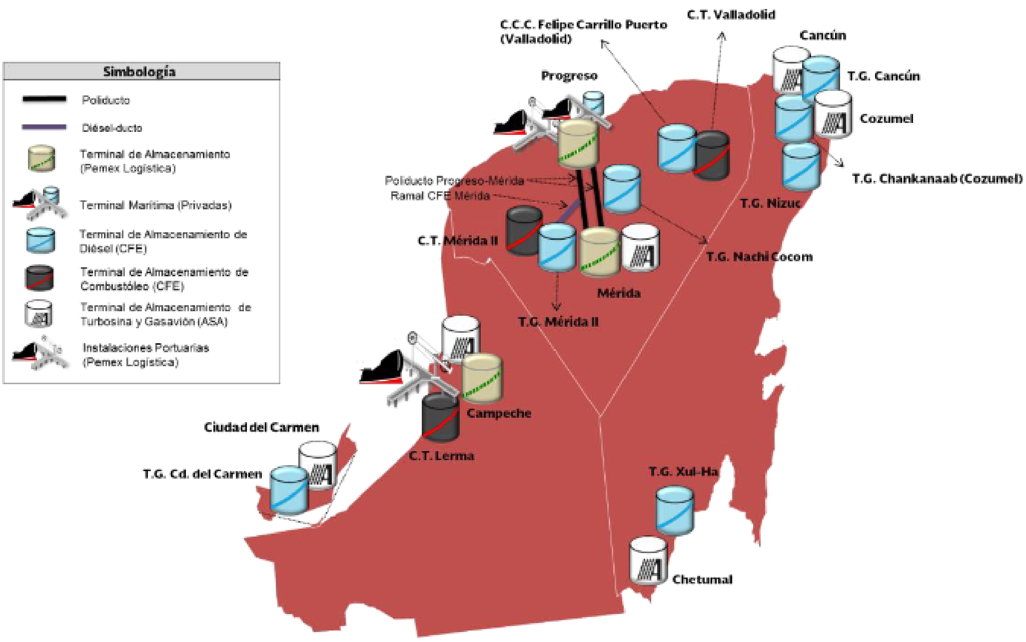


Figure 1.4: Fuel distribution infrastructure in Southeast Mexico (Secretaría de Energía 2018)

This procedure applies to the transportation of liquid fuels such as low and high-octane gasoline, diesel, and aviation fuel. From Merida, distribution to gas stations is handled by trunk tanks. The same applies to the international airport. These installations supply Merida and distribute fuels to Valladolid and Cancun, making this distribution network heavily reliant on highway transportation. The construction of a similar facility in Cancun has been considered to be connected by ducts to

Progreso and Merida (Cámara 2020), although no official announcement has been made.

1.5.2.2 Agricultural goods

Some importations of agricultural goods in bulk are destined to supply animal farms, one of the largest industries in the Yucatan state, shown in table 1.3.

Table 1.3: Bulk agricultural imports, port of Progreso

Bulk Agricultural import (tons)			
Product	2019	2020	2021
Soy	565,997	493,978	445,624
Corn	1,654,966	1,615,507	1,146,368
Wheat	229,863	262,006	286,090
Soy paste	0	13,199	11,931
Canola	51,535	72,848	46,676

1.5.2.3 Exports

According to Yucatan's Secretary of Economic Development and Labor (SEFOET), several industries export goods made in the state. Historically, one of the most important is the textile industry; other industries include jewelry, livestock, fruits, vegetables, and honey. In the first trimester of 2021, the largest export subsector was the clothing industry, followed by transport equipment manufacturing and the food industry (Gobierno de Yucatán 2021)

As these industries represent the most significant exporters in the state, they use not only the port of Progreso, but Yucatan industries also have the choice to transport by train or road.

1.5.3 Vehicles

1.5.3.1 Buses

For its implementation, the" Va y Ven" project selected a bus developed by Scania Mexico and Beccar, a Mexican bus manufacturer. The selected bus is a Scania K-250 chassis with a Beccar Urviabus bodywork, powered by a diesel, Euro 6 compliant engine (Transporte MX 2021). This bus model was previously used in Guadalajara and is a low-floor, single-deck rigid body unit that can accommodate up to 80 passengers (IMDUT 2021). The units have a length of 12 meters, a height of 3.2 meters, and a width of 2.43 meters (BECCAR 2021).

Figure 1.5: Unit used in the ”Va y ven” Route

Although the cost per unit for the ”Va y Ven” project is currently unknown, in 2019, an average 40-foot conventional diesel bus cost between \$460,000 to \$490,000, while an average compressed natural gas bus cost between \$540,000 to \$580,000. In comparison, a hydrogen bus could cost up to \$1.3 million. Projections indicate that the cost per unit could be around £ 650,000 for orders of tens of vehicles, similar to the JIVE project’s costs.

Bus manufacturers offer the same bodywork product powered by different energy sources and powertrains. Diesel and compressed natural gas are popular choices, while diesel-battery hybrids have become a common replacement for these. Products that share components and construction lines are subject to the economy of scale effects on shared processes and parts. New Flyer’s Xcelsior line is an example of this. It offers 42 and 60 ft versions of buses powered by diesel, com- pressed natural gas, hybrid, battery-electric, fuel-cell electric, and even a trolleybus version. Figure 1.6 displays some of these options (New Flyer 2019). For comparison purposes, we will focus on the Xcelsior Charge H_2, which is powered by hydrogen fuel cells and produced by New Flyer. Table 1.4 summarizes its characteristics.

Figure 1.6: New Flyer’s Xcelsior family brochure

Table 1.4: Characteristics of the selected bus (Eudy et al. 2021; New Flyer 2021)

Characteristics of Charge H2 Bus	
Length	12.5 m
Width	2.6 m
Height	3.3 m
Step height	254-356 mm
Tire size	305/70R22.5
Propulsion	Siemens ELFA2 EDS
Power	160 kW
Torque	1,033 lb-ft
Seats	40
Standees	42
Fuel cell	Ballard FCvelocity-HD85
Net power	85 kW
Hydrogen storage	37.5 kg
Fuel economy	7.17 kg/100km
Range*	523 km

*Calculated from Fuel economy and onboard hydrogen storage

Complementary infrastructure may be already in place, as the proposed FCB route would be the same as the ”Va y Ven” project; designated bus lanes and stops, as well as pedestrian crossings and bridges, have been already built, intermodal exchanges and stations could be constructed in the future to service a larger number of passengers. Furthermore, adding hydrogen units to the project assumes no new depot or other administrative facilities are needed.

1.5.3.2 Fuel cell cargo trucks

According to reports, fuel cell trucks are expected to find their exclusive use in long-haul transport for cargo and freight. This is because fuel cell technology is lighter than equivalent battery technology providing a longer distance between refueling stops and zero tailpipe emissions. However, this is likely to occur when the price of hydrogen is below USD $7/kgH_2$ (International Energy Agency 2019).

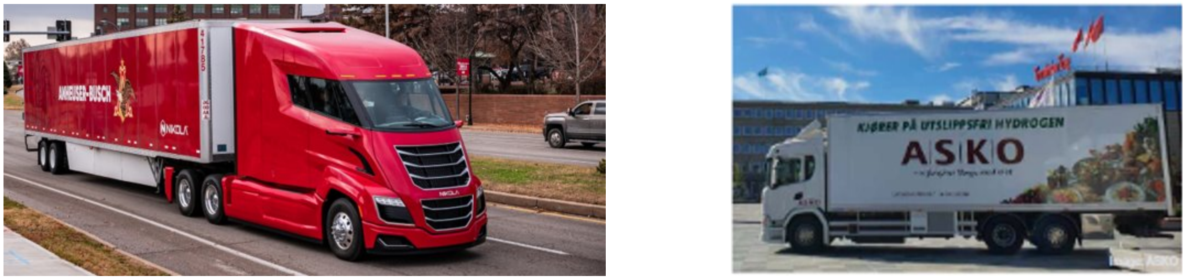
As stated before, the sector that could drive the adoption of FCVs in the cargo and freight industry in the region is aviation fuel transportation from Progreso to Cancun and Merida airports. Similarly to other industries, the cargo and freight sector is classified into different categories and limitations, with trucks being limited depending on their classification. In Mexico, highways are also classified, restricting the cargo that can be transported. Trucks classified as T3-S2-R4 can transport up to 66.5 tons (SCT 2017), with tanker trucks typically carrying 62,000L of fuel, figure 1.7 shows a typical fuel transport truck in a T3-S2-R4 configuration.

Table 1.5: Classification and weight limits of heavy trucks (SCT 2017)

Classification of heavy trucks			
Type	Axles	Tyres	Maximun weight (tons)
T2-S1-R2	5	18	47.5
T3-S1-R2	6	22	56.0
T3-S2-R2	7	26	60.5
T3-S2-R3	8	30	63.0
T3-S2-R4	9	34	66.5
T3-S3-S2	8	30	60.0


Figure 1.7: Example of a T3-S2-R4 tanker truck

Heavy-duty and light-duty FC-based trucks are specifically engineered and evaluated for commercial applications that vary depending on the transportation sector's specificities, infrastructure, and policies. Some differences exist between Europe and North America, where diverse demands have resulted in different designs. In Europe, the need for fast and shorter routes and multiple destinations has led to the development of rigid 4x2 trucks. In contrast, in the US, the requirement for long-distance and heavy load hauling has resulted in the design and manufacture of 6x4 tractor trucks. This difference in design can be observed in figure 1.8.



(a) FC Truck: Tractor in a 6x4 configuration, America

(b) FC Truck: Rigid in a 4x2 configuration, Europe

Figure 1.8: FC Truck configuration Examples

In line with the transport sector's specific needs, Mexico's policies and regulations for cargo transport generally align with those of the United States. Hence, a comparable strategy for fuel cell vehicles (FCVs) can be anticipated in this context. We analyzed a vehicle with similar characteristics, as outlined in Table 1.4. Mexican law and policy usually mirror that of the US, therefore, a similar approach to FCVs for cargo trucks could be expected, characteristics shown in table 1.6.

Table 1.6: Characteristics of the selected truck

Characteristics of Selected cargo hydrogen truck	
Propulsion	Nikola E
Power-Axle	160 kW
Torque	1,033 lb-ft
Seats	40
Standees	42
Fuel cell	Bosch FC
Net power	240 kW
Hydrogen storage	81 kg
Fuel economy	9 kg/100km
Range*	900 km

*Calculated from Fuel economy and onboard hydrogen storage

1.6 Fuel cell transportation previous studies

This work focuses on evaluating the feasibility of a new project that combines public transportation and cargo transport of goods. While such a proposal has not yet been implemented in Mexico, there have been several successful projects worldwide that provide valuable insights into their impacts and potential benefits.

For instance, a study conducted in Zhangjiakou, China, examined the implementation of hydrogen-powered public transport (G. Zhang et al. 2020). The study investigated three different bus routes in the city, each ranging from 10 to 14 kilometers in length. The fleet consisted of 74 hydrogen buses, with varying lengths of 10 and 12 meters and hydrogen tank capacities of 20 and 25 kilograms. The primary objective of the study was to conduct a life cycle analysis of the buses within the transportation system, taking into account the adoption of a green hydrogen refueling strategy.

The findings of the study revealed several key insights. Firstly, despite the availability of various government subsidies, the capital investment required for the implementation of the hydrogen bus fleet remained relatively high. This highlights the importance of financial support and incentives to facilitate the adoption of hydrogen-based transportation systems. Secondly, in the short term, the profitability of the project was relatively low. However, the study acknowledged the potential for increased profitability in the future, as hydrogen transit becomes widespread and economies of scale are realized, it was projected that by 2030, the price of hydrogen in the region could fall below 5 USD per kilogram, contributing to improved economic viability and attractiveness of green hydrogen public transport.

1.7 Hypothesis

A hydrogen value chain for usage in public transport and cargo using renewable energy for its production is competitive with current technologies in use across Merida Yucatan.

1.8 General objective

To propose an urban transport project based on hydrogen technology in Mérida, Yucatán, and the integration of regional cargo transport.

1.9 Particular objectives

1. To propose technology and supplier of vehicles.
2. To present pilot route proposals for public transport and cargo.
3. To estimate the number of vehicles for service in the project.
4. To evaluate hydrogen demand.
5. To propose a supply chain project.
6. To design recharge infrastructure.
7. To estimate the cost of the project.

CHAPTER 2

METHODOLOGY

To successfully introduce hydrogen-based technology into the current transportation system in Mexico, it was necessary to address the lack of government support and planning for necessary infrastructure (H2LAC 2020). By 2021, several Latin American countries had already developed roadmaps for hydrogen technology adoption (Minenergía 2021; Ministerio de Energía 2020; Viceministerio de Minas y Energía 2021), but Mexico had not yet created a public plan for the introduction of green hydrogen into the national energy grid. However, in 2022, the Mexican Hydrogen Association released a document that promoted hydrogen as a means to decarbonize the national economy, outlined sector-specific strategies, and identified actions in several strategic lines (Mexican Hydrogen Association 2022).). In 2021, chapter 5 of the Program for the Development of the National Power System (PRODESEN) briefly mentioned the possibility of replacing natural gas turbines with green hydrogen-fueled turbines to promote the adoption of greener technologies.

Overall, developing a comprehensive transportation plan adopting hydrogen-based technology in Mexico, and specifically in Yucatan, requires careful consideration of various factors, including the identification of different elements of the hydrogen value chain, such as vehicles, infrastructure for hydrogen production, treatment, distribution, and refueling stations, as shown in Figure 2.1.

As the information-gathering phase progressed, a careful selection of options for vehicles and infrastructure was made to study them in-depth and consider their potential use in a case study for services. The proposed routes included urban transit and regional cargo, with Mérida as a hub connecting various regions in the Yucatán Peninsula, southwestern Mexico, the entire country, and international travel and shipping. Proposals for pilot projects were developed considering the particularities and possibilities for urban transit and cargo transport. A wide range of factors was considered for both projects, including fleet size, hydrogen requirements, infrastructure, supply chain, cost projections, and the benefits of these proposals, such as their positive environmental impact and the reduction of emissions compared to conventional transportation methods. A crucial aspect considered was the social impact of such projects, as efficient and affordable mobility is essential to society, and people need to feel safe and confident in the transport systems they use.

Detailed studies of socioeconomic mobility had been conducted for Merida's Metropolitan zone, similar to those made for larger cities such as Mexico City, Guadalajara, and Monterrey. These studies were undertaken to plan the development of infrastructure and assess the mobility needs of the population.

As depicted in Figure 2.2, the project methodology was designed to specifically target the region's fuel transportation and public transport sectors. The number of vehicles needed to operate the routes was estimated in the first phase, additionally determining their technical specifications and fueling requirements. To ensure the hydrogen produced was classified as green hydrogen, solar power plants were proposed to supply the energy needed for the electrolyzers.

Based on these estimations, the project components were proposed and integrated, primarily focusing on identifying and addressing any potential challenges that might arise, such as the legal framework, environmental and societal impacts, and project costs. In the project´s final phase, the transportation, hydrogen production, and electricity generation sections were evaluated to determine their value and challenges.

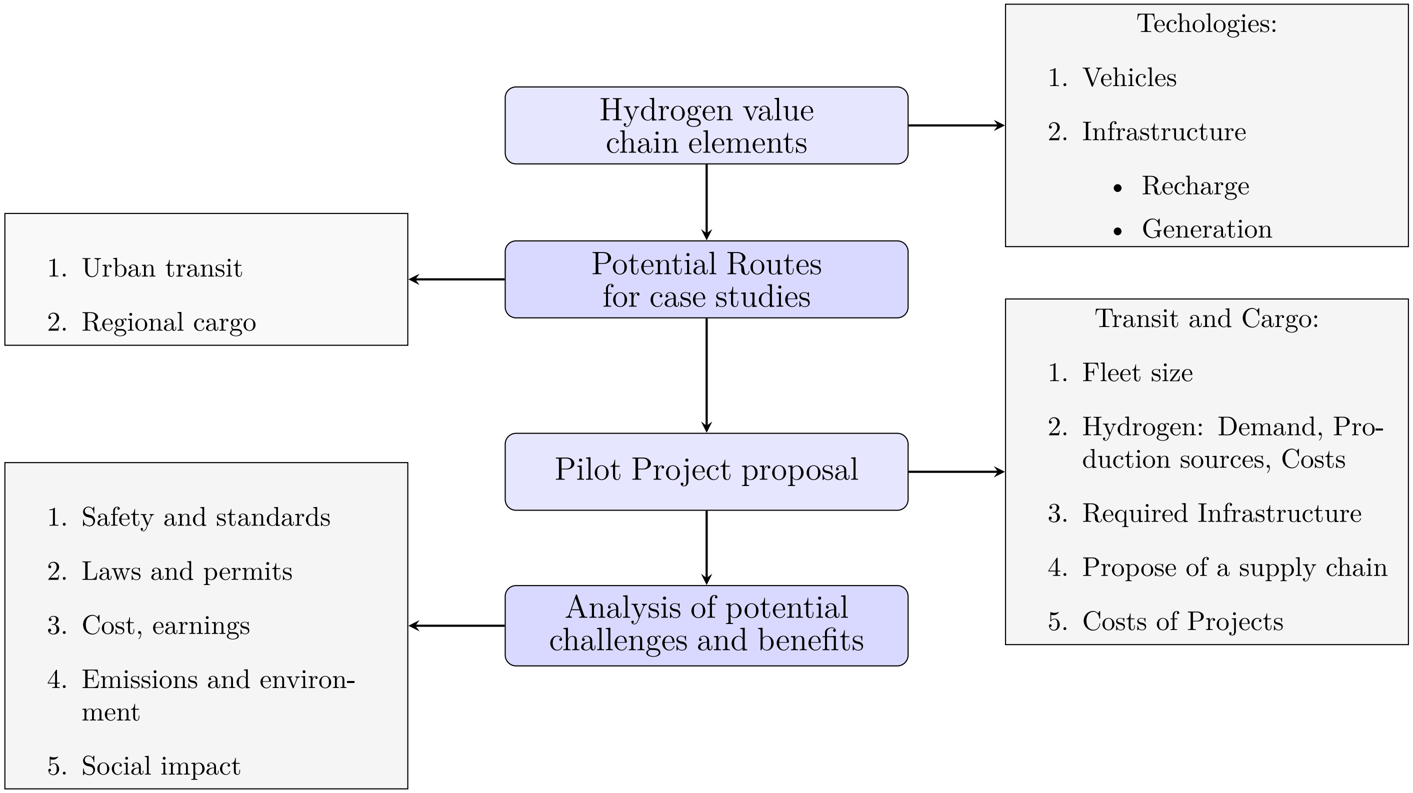


Figure 2.1: Considerations of the project

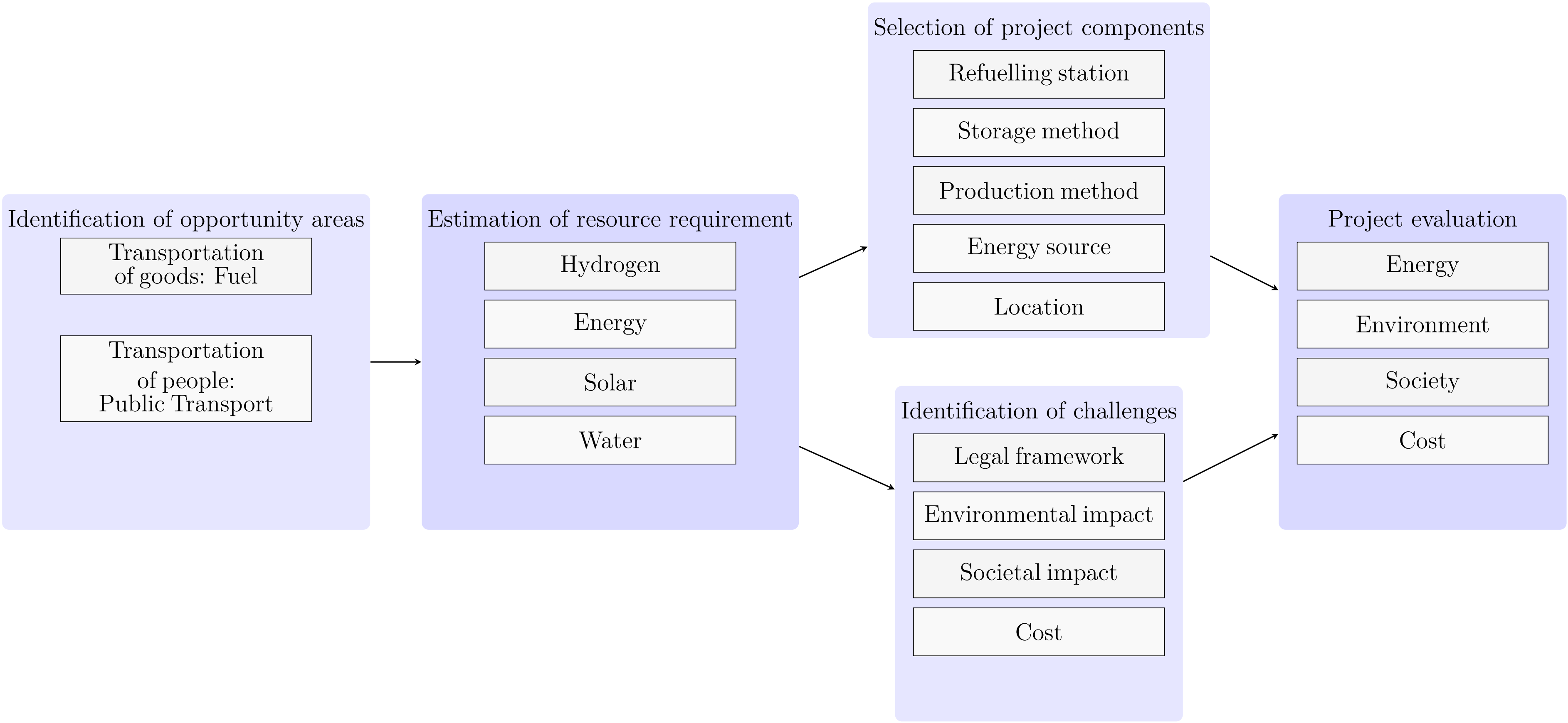


Figure 2.2: Methodology

2.1 Selection of transportation routes

The Secretariat of Economic Development and Labor (SEFOET) has already delineated the “Va y Ven” bus route. Several significant factors will impact the project’s implementation, including the route’s length of 50 km, which entails 69 stops (34 and 35 in each direction) and an average speed of approximately 60 km/h. The daily operation is expected to cater to around 12,000 passengers. Table 2.3a shows the details of the route selected, the distance traveled by an on-duty bus is 1050 km, after final service would have done 1080 km.

The study of FCTs has focused on the transportation of aviation fuel along the Merida-Cancun route. This route is crucial for delivering fuel to the Quintana Roo state, which lacks infrastructure such as pipelines or ports. However, Cancun International Airport, second-largest in the country, is located in this state. Therefore, fuel transported by road is essential to support operations. Table 2.3b provides the route’s characteristics, total distance is 700 km, taking into account any deviations, it is estimated that a fully fueled truck is capable of doing 720 km.

Figure 2.3: Selected routes characteristics

(a) Characteristics of the public transport route

Va y Ven Route	
Route	Va y Ven
Travel time	50 min
Work hours	18 h
Work days	7
Trip distance	50 km
Trips per day	21
Daily distance	1080 km

(b) Characteristics of the cargo transport route

Merida Cancun route	
Route	Mexico 180D
Travel time	7 h 46 min
Work hours	8 h
Work days	7
Trip distance	700 km
Trips per day	1
Daily distance	720 km

2.2 Project sections

The project has three sections: electrical energy generation, hydrogen production and refueling shown in 2.4. The energy section is separated from production and refueling, making possible to fully supply the total energy requirement for the other sections because the photovoltaic power plant can be as large as it is needed.

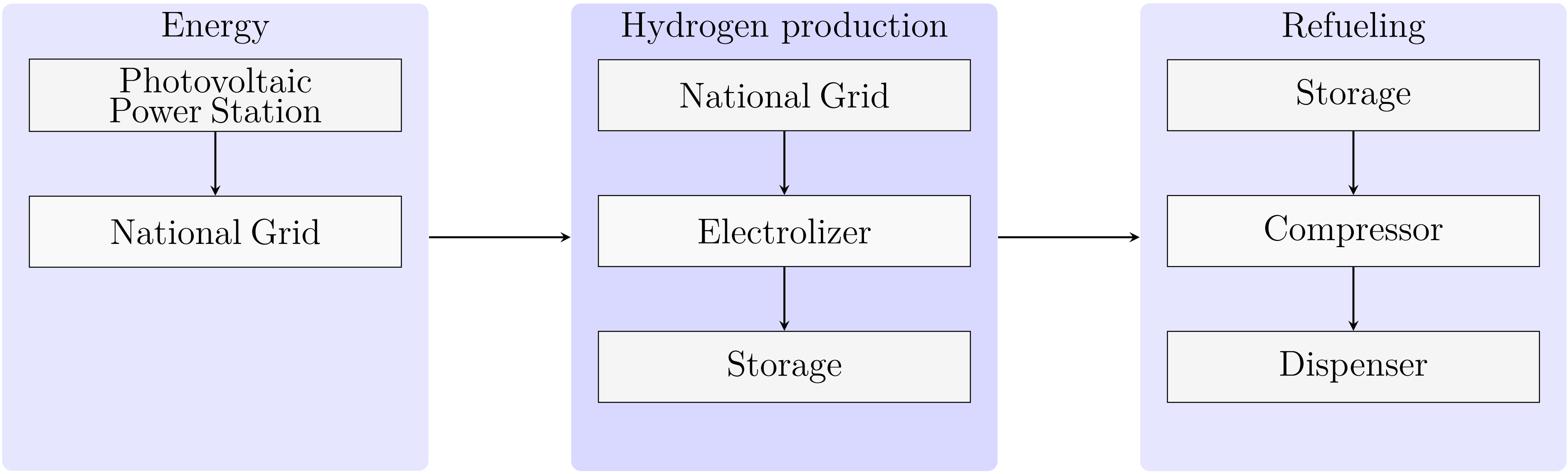


Figure 2.4: Project Sections

2.2.1 Vehicles

The characteristics of each type of unit, buses, and trucks, are shown in Tables 1.4 and Table 1.6, for the bus selection, similar to existing units in the ”Va y Ven” project, while the truck selection was constrained by law regulations about allowed maximum cargo capacity. The range for the selected bus is calculated by dividing the fuel economy times the amount of on board storage, and multiplying the result by 100, as the fuel economy is expressed as the amount of fuel needed to drive 100 km, the result shows that a stop for refueling would be needed for the public transportation project. As for the cargo transportation, the range is enough for the trip made from Merida to Cancun and back. The on board storage of 81 kg, and consuming 9 kg per 100 km, a unit of this characteristics would be able to drive up to 900 km in total.

In order to determine the energy requirements for the project, it was necessary first to establish the number of fuel cell-based vehicles and their specific characteristics. The project proposal for the cargo transportation aims to have a transport capacity of 20% based on the current transportation capabilities, 3 million liters of Jet-A1 aviation fuel are needed daily by Cancun International Airport, the transportation demand would be of 600,000 liters, transported by 10 FCTs. For public transportation project, there are 22 units on the peripheral circuit, a 20% of its transportation capacity would be serviced by 5 vehicles, the composition of each fleet is presented in Table 2.1.

Table 2.1: Fleet calculation

Fleet Calculation			
Cargo Transport		Public Transport	
Jet A-1 Requirement, Daily[a] (l)	2,955,357	Present units[b]	22
Jet A-1 Capacity per tanker truck (l)	62,000	Passenger Capacity per bus	82
Tanker truck fleet	10	Bus fleet[c]	5

Calculated from [a]Cepeda 2018 and [b]Abreu 2021. [c] Each unit makes several trips in a work day

2.2.2 Hydrogen requirement and electrolyzer characteristics

The total hydrogen requirement for the project can be calculated by adding the hydrogen requirement for each individual bus or cargo truck based on their on-board fuel capacity and route characteristics. Equation 2.1illustrates the calculation method, where H_{To} represents the total hydrogen requirement, H_B and H_T represent the hydrogen requirement for a single bus and cargo truck, respectively, PT and TT represent the number of buses and cargo trucks in the fleet. To ensure adequate fuel supply, production is estimated to provide fuel for two days, with capacity reached in 14 days, resulting in a 1.07 production modifier.

$$H_{To} = (1.07) * [(H_B * PT) + (H_T * TT)] \tag{2.1}$$

A Siemens SILYZER 300 was chosen because it can produce up to 340 kg of hydrogen per hour. Its characteristics are shown in Table 2.2. It was selected because of its availability and modularity.

Table 2.2: Characteristics of the selected electrolyzer(Siemens 2019)

Characteristics of Selected Electrolyzer	
Name	Silyzer 300
Nominal capacity (kgH/h)	340
Nominal energy requirement (kWh)	17500
Nominal water requirement (L/kgH)	10

2.2.3 Water requirement

The availability of water was a crucial consideration for the project. Yucatan's state water resources are better than other regions in Mexico since it has no water deficit issues (Graniel C 2022). However, the project could have procured already processed water and treated it as a feedstock; a water treatment option was preferred. It was assumed that the state water administration, Junta de Agua Potable y Alcantarillado de Yucatán (JAPAY),would provide the necessary water resources. However, the water would require pre-treatment before usage. The total water consumption was calculated using equation 2.2, where W_{To} represented the total amount of water, and W_e denotes the water required to produce one kilogram of hydrogen according to manufacturer's specifications.

$$W_{To} = W_e * H_{To} \tag{2.2}$$

The water treatment method chosen for the project was Capacitive Deionization (CDI), which involves the application of an electric potential difference between electrodes to remove particles and compounds from a flowing water stream, thereby reducing pollutants and softening the water. As the water in Yucatan is considered Hard Water, with varying hardness levels ranging from 336 to 1321 ppm (Medina-Escobedo et al. 1997), it required treatment for use in industrial settings.), it requires treatment for its use in industrial settings. The energy required to soften the water was assumed to be 0.439 W/L (Liu, Shanbhag, T. V. Bartholomew, et al. 2021), and a water hardness value of 0.8285 g/l was assumed.

The energy required to treat the water, E_{Wt}, is calculated in equation 2.43, W_{Ha} is the water hardness and E_{De} is the energy required to deionize water per gram of ions of sodium chloride diluted, a common water hardness index.

$$E_{Wt} = W_{Ha} * E_{De} \tag{2.3}$$

2.2.4 Energy requirement and solar resource

Each component´s energy demands must be considered to estimate the project’s required energy. In the case of hydrogen production, energy is needed not only for the electrolysis of water but also for the treatment of the municipal water supply.

The total energy required for the project can be calculated using Equation 2.4. This equation considers the energy requirements for each component of the project. Specifically, E_{Hy} represents the electrolyzer required energy to produce one kilogram of hydrogen multiplied by the total amount of hydrogen produced,H_{To}. The energy required by the refueling station, E_R, can be calculated using the refueling station design software. Finally, the energy needed to treat the municipal water supply, E_{Wt}, is expressed as the energy required per liter of water used, times the amount of water required, W_{To}.

$$E_{To} = (E_{Hy} * H_{To}) + E_R + (E_{Wt} * W_{To}) \tag{2.4}$$

Moreover, the total energy required was estimated annually to account for the yearly variability in available solar resources. This ensured that the solar power plant design was robust enough to handle fluctuations in resource availability for a year. The available solar resource at the project location was needed to design the photovoltaic power plant. The online tool PVWatts, developed by NREL, was used for this purpose. PVWatts combines the National Solar Radiation Database or a similar database with the location-specific information to estimate the energy output of a photovoltaic installation. Custom installation parameters such as DC installed capacity, module and array type, system losses, tilt, and azimuth can also be input. In this study, the installation parameters were held constant, as shown in Table 2.4. The monthly solar resource available is presented in Table 2.3.

Table 2.3: Solar resource, typical meteorological year (1998-2019) (NREL 2022a)

Solar resource availability	
Month	Resource ($kWh/m^2/day$)
January	5.23
February	5.89
March	6.49
April	6.69
May	6.35
June	5.67
July	6.04
August	6.12
September	6.00
October	5.65
November	5.42
December	5.15
Average	5.89

Table 2.4: Parameters of the installation (NREL 2022b)

Parameters input on PVWatts	
Concept	Value
Solar resource average	5.89 kWh/m^2/day
Module type	Standard
Array type	Fixed, open rack
System losses (%)	14.08
Tilt (deg)	20
Azimuth (deg)	180
AC to DC ratio	1.2
Inverter efficiency (%)	96

2.3 Environmental impact estimation

Environmental impact was evaluated by comparing emission generation between technologies, and three cases were studied, internal combustion engine vehicles fueled by diesel and fuel cell vehicles using hydrogen produced using the national grid, or solar photovoltaics as an energy source. This classification was created in order to compare the technologies evaluated in this study. Technology description is shown in Table 2.5.

Table 2.5: Technology description

Technologies description		
Sector	Technology	Fuel source
Public transport	Fuel cell	National Grid
	Fuel cell	Photovoltaic
	Internal Combustion	Diesel
Cargo	Fuel cell	National Grid
	Fuel cell	Photovoltaic
	Internal Combustion	Diesel

The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model,was used to calculate emissions per kilometer. The Argonne National developed the model laboratory performs the life cycle analysis by simulating the energy use and emissions of different combinations of technologies and energy sources, separating fuel and vehicle processes into two categories for simulation (Argonne National Laboratory 2020).

Table 2.6: National Grid 2018 composition and growth projection (2024,2030) Secretaría de energía 2020

National Grid Composition						
Energy source	2018		2024		2030	
	GWH	%	GWH	%	GWH	%
Bioenergy	599.00	0.19%	1,051.06	0.29%	1,289.98	0.31%
Coal	29,762.30	9.38%	29,261.67	7.94%	31,418.71	7.48%
Natural Gas	191,848.57	60.47%	193,994.36	52.62%	214,573.80	51.08%
LP Gas	417.30	0.13%	410.28	0.11%	440.52	0.10%
Residual Gas	2,037.03	0.64%	2,002.77	0.54%	2,150.40	0.51%
Fuel Oil	20,089.14	6.33%	19,751.22	5.36%	21,207.19	5.05%
Diesel	6,549.66	2.06%	6,439.49	1.75%	6,914.18	1.65%
Wind	12,434.00	3.92%	21,817.91	5.92%	26,777.40	6.37%
Geothermal	5,375.00	1.69%	9,431.50	2.56%	11,575.40	2.76%
Water	32,436.00	10.22%	56,915.38	15.44%	69,852.95	16.63%
Uranium	13,555.00	4.27%	23,784.93	6.45%	29,191.54	6.95%
Solar(PV)	2,175.00	0.69%	3,816.47	1.04%	4,684.00	1.12%
Total	317,278.00	100.00%	368,677.04	100.00%	420,076.07	100.00%

Made from information published by SENER

The GREET Model estimates the outputs of processes based on a database. The national grid composition was created for electricity use, as shown in Table 2.6. On the other hand, the supply chain of diesel was also recreated. It was traced to be transported from Galveston, Texas, USA, to Pajaritos, Veracruz, Mexico, by tanker. From there, it was transported to Progreso, also by tanker, and finally transported to Merida by polyduct. The software requires this information to approximate the energy required and emissions produced by different technologies at each step of the life of a vehicle:

- Well to pump: it encompasses the extraction, refinement, transport, and distribution of fuel.
- Operation: the energy and emissions related to the vehicle operation, tailpipe emissions.
- Manufacture, Maintenance and Service: vehicle manufacture, subsequent maintenance, and related products such as fluids and batteries.

2.4 Societal impact estimation

The social cost of the project is difficult to estimate. Several methodologies are used worldwide to estimate the impacts, but not all sectors of a given society are affected equally. A 123 USD per ton of CO_2 cost was used to estimate the societal impact. The assessment from the Environmental Protection Agency (EPA) included the cost of agricultural productivity decline, public health issues, property damages, and energy system costs variations (Environmental Protection Agency 2021). The conversion of CO_2 into monetary terms allows a comparison to other aspects of analysis of a certain project, although it sums up all societal impacts as a price, different sectors of society would be affected in diverse ways, not necessarily reflected in a price tag.

2.5 Financial analysis

In order to compare the feasibility of the project, the Net Present Value (NVP) and the Internal Rate of Return (IRR) were used. The first indicates, in simpler terms, the time value of money, an investment, accounting for time, cash flows, and value discount, making it possible to evaluate a project as a potential investment quickly should the NVP bbe positive and how big the value of the project would be. On the other hand, IRR was used to determine the profitability of the investment. It also communicates the rate that makes the NVP net zero. The higher the IRR was, the higher the project's profitability was, and it was used to compare the competing investments.

For comparison, each section of the project was evaluated separately. The energy produced by the photovoltaic power plant was assumed to be sold at the average of a solar plant in Mexico, close to 0.045 USD/kWh, according to the last long-term energy auction (CENACE 2015),and a 447 USD/kW investment is considered, a 37% decrease from the 2018 level of capital cost needed for solar power plant (INECC et al. 2020). Hydrogen production and refueling were evaluated independently of each other, and it was assumed that hydrogen was sold at the determined price by Heavy-Duty Refueling Station Analysis Model (HDRSAM) and Hydrogen Analysis Production Model (H2A).

Finally, public transport was evaluated assuming the project would fully serve a further fifth of the existing system. Each fare would cost 0.83 USD (15 MXN), and it had to consider the government subsidy that gave the operator up to 1.03 USD per kilometer traveled (Gobierno de Yucatan 2021). Capital costs and maintenance of the units, permits, fuel, and salaries for the new drivers were the cost of the service. For cargo transport, the income was determined by the cost of transportation, 0.06 USD per kilometer-ton, assuming 62 tonnages per cargo (Herrera 2021).

CHAPTER 3

RESULTS AND DISCUSSIONS

3.1 Hydrogen requirement and production

For the public transport service, the daily hydrogen required amounts to 387.11 kg or 77.42 kg per unit, as for the cargo trucks, each unit requires 64.80 kg of hydrogen daily, and the estimated daily demand for the complete fuel transportation service is 648.00 kg. These figures are determined based on the distance driven, the number of vehicles, and fuel consumption.

The total daily hydrogen requirement for the entire fleet is 1035.11 kg, comprising 15 units, 5 buses, and 10 cargo trucks. In order to ensure an uninterrupted fuel supply, additional hydrogen storage capacity is required, which is set to double the daily amount needed. This allows to halt the hydrogen production for two days, and the storage capacity can be achieved within 14 days. Therefore, the daily hydrogen requirement for the project is set at 1109.04 kg, shown in Table 3.1.

Table 3.1: Hydrogen requirement

Hydrogen requirement estimation		
Concept	Type of vehicle	
	Bus	Cargo
Hydrogen requirement, daily per vehicle (kg)	77.422	64.800
Number of vehicles	5	10
Hydrogen requirement, daily (kg)	387.11	648.00

3.1.1 Hydrogen storage

Compressed hydrogen will be chosen as the storage method, at 350 and 700 bar in a 60-40 ratio. The required tank volume for storage at 350 bar would be 283.76 m^3, while the tank size at 700 bar would be 117.56 m^3.

3.2 Refueling stations

In hydrogen fuel cell vehicles, refueling is a critical component that must be efficient and reliable to promote the adoption of the technology. Cascade and booster refueling stations are two designs implemented in the industry. Cascade stations use multiple tanks with different pressures to allow for a complete refueling process without losing speed or requiring an intermediate compressor. In contrast, booster stations have a compressor unit between the storage and the dispatcher to achieve the necessary pressure to maintain the refill speed and fully refuel the vehicle's tank.

The refueling station design shown in Figure 3.1 incorporates a cascade system that bypasses the need for a booster compressor while utilizing a mid-pressure storage tank. The first compression stage takes the hydrogen produced by the electrolyzer at 20 bar and compresses it up to 500 bar. Further compression is then required to reach 880 bar for faster recharge rates.

To design the refueling station, Heavy-Duty Refueling Station Analysis Model (HDRSAM), a program developed by NREL, was utilized to approximate the energy requirement while considering subsystems such as cooling and dispatching. The energy requirement for the refueling station is shown in Table 3.2.

Table 3.2: Energy requirement of the refueling station

Energy requirement (kWh)	
Main compressors	3,167,933
Cooling	20,655
Total	3,188,588

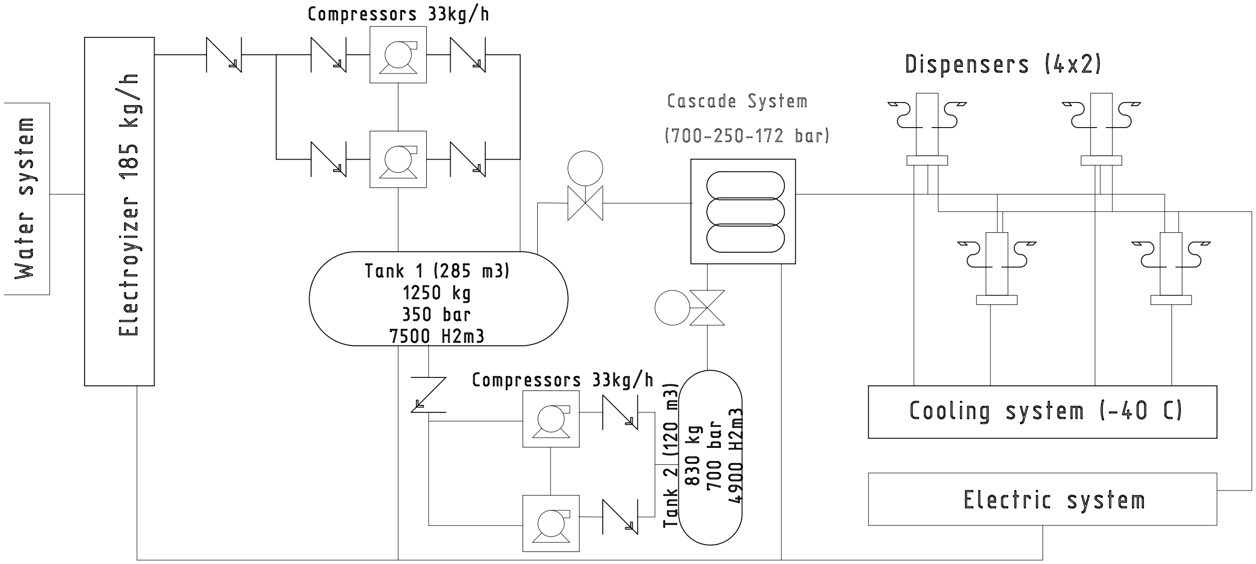


Figure 3.1: Refueling Station Design

3.3 Energy and water requirement

The SILYZER 300 electrolyzer can produce up to 340 kg of hydrogen per hour, consuming 17.5 MW of electricity and 10 L of water per kilogram of hydrogen produced (Siemens 2019). Based on the selected electrolyzer, hydrogen production's energy and water requirements can be calculated, as shown in Table 3.3.

Table 3.3: Water and electricity requirement estimation for the project

Resource requirement estimation	
Electric requirement for H_2 production (kWh/kg)	51.47
Water requirement for H_2 production (L/kg)	10.000
Daily electric requirement (kWh)	57083.15
Daily water requirement (L)	11,090.44

The daily energy requirement for hydrogen production is 57,083.15 kWh, assuming optimal operating conditions without significant efficiency losses; this energy is fed to the electrolyzer throughout the day, producing the required amount of hydrogen. The hydrogen production and energy calculations for a typical day are presented in Table 3.4, which assumes six hours of constant production.

Table 3.4: Energy requirement for Hydrogen production, hourly

Hourly estimation	
Concept	Value
Daily electric requirement for H2 production (kWh)	57,083.15
Working hours	6
Electric capacity (kW)	9513.86
Hourly H_2 production (kg/h)	184.84

Moreover, it is crucial to consider the energy required to pressurize hydrogen, as it constitutes a crucial component of the project. According to the United States Department of Energy (Gardiner 2009), 2.23 kWh/kg H_2 is necessary to compress gas up to 350 bar, while 3 kWh/kg H_2 is required to reach 700 bar. Assuming a compression ratio of 60% at 350 bar and 40% at 700 bar for the total volume of hydrogen, the total compression energy would be 2814.753 kWh, furthermore the energy required to treat the water used is 4869.868 W per day. For daily operation with a six-hour shift, the energy requirement for the hydrogen production section of the project amounts to 59,902.78 kWh.

3.4 Energy production

We estimated the total energy requirement of the project as the annual sum that needs to be supplied by the power plant. The annual energy requirement of the project is presented in Table 3.5.

Table 3.5: Annualized energy requirement

The annualized energy requirement of the project	
Project part	Energy requirement (kWh/y)
Refueling station	22,513,457.62
Electrolyzer	3,188,588.16
Water treatment	1,777.50
Total	25,703,823.28

Using PVWatts, an online tool provided by NREL, to estimate the energy output of a photovoltaic installation is a standard practice in the industry. PVWatts utilizes the National Solar Radiation Database or a similar database, combined with location-specific information, to estimate energy output. Custom parameters for the installation can also be input, such as DC installed capacity, module and array type, system losses, tilt, and azimuth. The monthly and total energy output, as well as the monthly solar resource, are presented in Table 3.6

The proposed solar power plant has a similar scale to other solar projects in the state. For example, the San Ignacio photovoltaic power plant, built by Jinko Solar in the municipality of Progreso, has an installed capacity of 18 Megawatts (Juan 2019). As the power production part of the project is separated from hydrogen production and refueling, it is necessary to consider that auxiliary infrastructure could be required to connect to the national grid.

Table 3.6: Energy output of the solar installation

Solar output		
Month	Resource ($kWh/m^2/day$)	Energy (kWh)
January	5.23	1,983,823
February	5.89	2,012,314
March	6.49	2,410,717
April	6.69	2,376,754
May	6.35	2,360,969
June	5.67	2,038,723
July	6.04	2,239,488
August	6.12	2,291,372
September	6.00	2,188,879
October	5.65	2,155,400
November	5.42	2,012,740
December	5.15	1,988,052
Total	5.89	26,059,231

3.5 Costs

The economic aspects of a refueling station can be calculated using the Heavy-Duty Refueling Station Analysis Model (HDRSAM) software from NREL, which considers the size of the heavy vehicle fleet, its hydrogen requirement, and the hourly refill schedule. The software is based on various assumptions made by NREL, such as the cost and capabilities of the compressor and cooler systems and costs predictions for the technology. Some of these costs are based on similar technologies used in other sectors. For instance, the dispensers are assumed to be similar to those used for natural gas. The program also automates some aspects of the design of the refueling station and assumes that the feedstock of gaseous hydrogen is provided to the site and stored in several low-pressure vessels. The designed HRS assumes that the hydrogen is produced by an electrolyzer and compressed to a higher pressure to increase its energy density rather than compressing only to refill the cascade system. However, it is important to note that the electrolyzer and its subsystems are not included in the program calculations.

Table 3.7: Costs

Costs of the project			
Section	Capital cost	Operating Costs	Feedstocks
Refueling station	$ 8,204,437.36	$ 322,978.87	$ 138,358.76
Electrolyzer	$ 2,738,324.33	$ 178,784.45	$ 763,772.72
Water treatment	$ 1,153.68	$ 161.52	$ 3,145.86
PV power plant	$5,780,000.00	$ 178,500.00	$–
FCB Fleet	$ 3,500,937.50	$ 441,622.26	$ 1,067,427.58
FCT Fleet	$ 3,595,000.00	$ 380,641.10	$ 1,503,909.19
Total	$ 23,819,852.88	$1,502,688.19	$ 905,277.34

The PEM module of the H2A: The Hydrogen Analysis Production Models are used to estimate the cost of the hydrogen production section of the project based on the previously calculated hydrogen requirements for the fleet. Water-related costs are calculated based on the cost of technology, as detailed by Liu and colleagues (Liu, Shanbhag, T. Bartholomew, et al. 2020), for the levelized cost of water-softening technology. All costs are presented in Table 3.7, and the feedstock costs for buses and trucks vary depending on the cost of hydrogen, as shown in the next section. The table displays the fleets' feedstock cost if hydrogen costs $7.55 per kilogram.

Capital costs include the resources needed to install and prepare the different sections of the project, including equipment purchase. Operating costs refer to the required resources to keep the sections of the project running, excluding energy and water. The costs related to these resources are considered in the feedstocks category.

3.5.1 Hydrogen cost

In order to estimate costs and revenues for public transport and cargo, it is necessary to determine a fair price for hydrogen production and processing using the H2A and HDRSAM models, which rely on input parameters such as the cost of technology, energy, and water. Additionally, a quick design of a refueling station is required based on project requirements, including the number of dispensers and the rate of refueling, as these factors determine the cost of the station. Figure 3.2 shows a breakdown of hydrogen costs, with ”P” tags representing production costs, ”R” referring to refueling costs, ”OM” standing for operation and maintenance costs, ”OV” representing other variable costs, and ”FD” referring to feedstock costs.

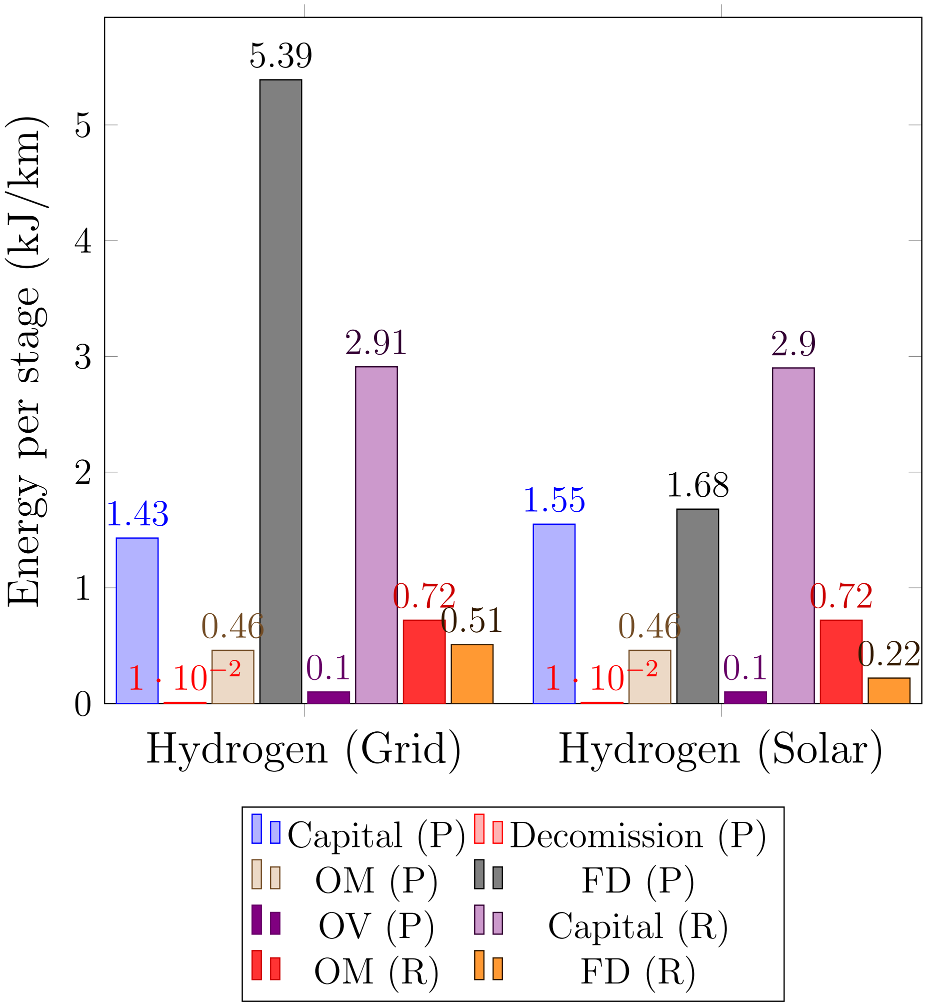


Figure 3.2: Hydrogen cost detailed

Two electricity sources were evaluated for hydrogen production: electricity from the grid and a solar photovoltaic installation. The cost of producing hydrogen using these sources are \$11.44 and \$7.55 per kilogram of H_2, respectively. . A detailed analysis of the findings revealed that, in the case of hydrogen produced from the grid, the feedstock cost accounts for the majority of the cost per kilogram obtained. On the other hand, for green hydrogen production, the capital costs of the refueling station represent the primary expense, while feedstock costs are lower in comparison.

3.6 Financial analysis

Each project section was evaluated individually to identify sectors that would not be financially or practically feasible based on the predetermined criteria. This in-depth analysis aimed to comprehensively understand each project section's strengths and weaknesses, enabling us to make informed decisions and develop viable solutions.

3.6.1 Solar power plant

Figure 3.3 presents the cumulative cash flow of our solar power plant, indicating a positive financial outlook for this project. Additionally, the IRR is 9.49%, while the NVP is $1,245,019.18. These results are reached because it is a renewable energy-producing project and a tax relief of the ISR on capital investment is available, offering a relatively quick breakeven time for investment, furthermore a stable energy production and its sale is considered, resulting in a constant revenue stream.

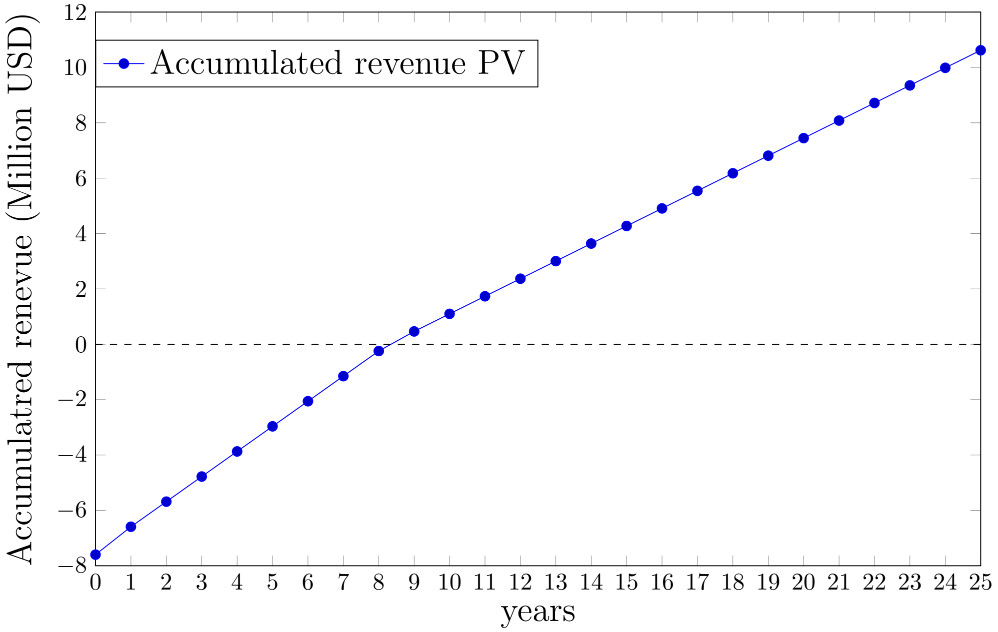


Figure 3.3: Cumulative revenue analysis, solar installation

However, we must also consider the potential impact on other project sectors, as increasing the price of energy sold in this sector, which would benefit its financial evaluation, may have negative consequences for other areas.

3.6.2 Hydrogen production

In Figure 3.4, the cumulative cash flow of the production sector of the project is presented, comparing the production of gray and green hydrogen from the grid and solar power, respectively. As mentioned earlier, the feedstocks required to produce the fuel constitute the majority of the production cost of hydrogen produced from grid electricity, and this cost is passed on to the consumer in the form of hydrogen pricing.

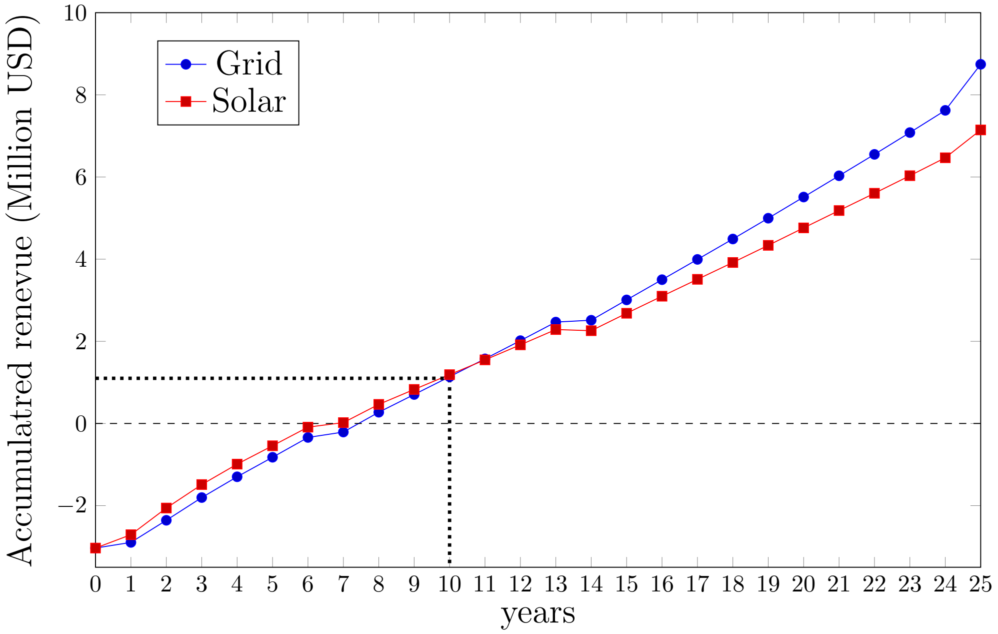


Figure 3.4: Cumulative revenue analysis, hydrogen production

An in-depth analysis of the graph shows that the production of gray hydrogen starts as a less profitable investment but gradually becomes the more profitable choice over time. By year 10, the gray hydrogen project outperforms the green hydrogen project by a slight margin. This is primarily due to the larger cost of hydrogen sold.

It should be noted that the cash flow analysis presented in the graph assumes a fair, fixed hydrogen price. This analysis provides a useful insight into the potential profitability of the project over time, highlighting the benefits of investing in renewable energy sources for hydrogen production, as it presents a lower price for subsequent sectors of the project.

The results of the financial indexes of Internal Rate of Return (IRR) and Net Present Value (NVP) for both the gray and green hydrogen production methods demonstrate the similarity of the two projects, with an identical IRR of 13.31%, and a NVP of $1,624,033.17 and $1,377,512.60 for the gray hydrogen and green hydrogen projects respectively. When viewed in isolation, this might suggest that gray hydrogen production, powered by the national grid, is a more prudent investment, given that its NVP is almost $300,000.00 more than that of the green hydrogen project, produced by solar power which results in $1,377,512.60, this comparison would not be taking into account further increases in costs for other sectors of the project.

3.6.3 Hydrogen refueling

In figure 3.5, the cumulative cash flow of both green and gray hydrogen production is displayed. The graph shows that both projects have a similar pattern, with green hydrogen reaching a positive cumulative cash flow by year 6 and gray hydrogen by year 7.

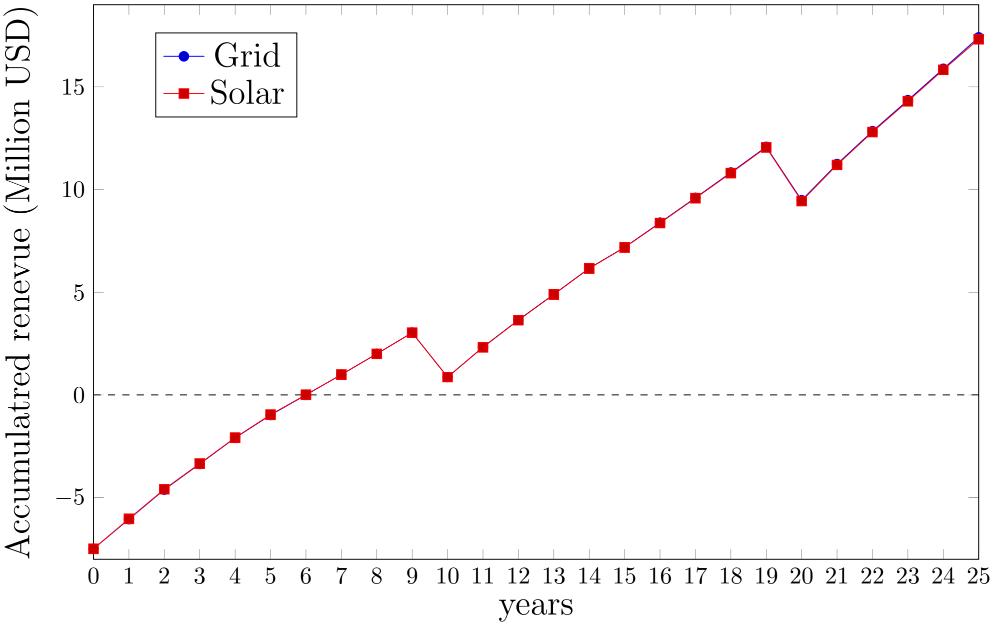


Figure 3.5: Cumulative revenue analysis, hydrogen refueling

However, due to the required maintenance investments, both projects experience a dip in accumulated cash in the 10th and 20th years. By the end of the evaluated timeframe, gray hydrogen has a slightly higher cumulative cash flow than green hydrogen, by nearly a hundred thousand dollars.

It is important to note that the fair pricing assumption of hydrogen refueling being fully paid at 4.15 USD/kg and 3.85 USD/kg for gray and green hydrogen may lead to the false impression that gray hydrogen production is a more favorable investment option. However, this assumption passes the cost of fuel to the transport sector of the project, and a deeper analysis is required to evaluate the project´s overall profitability.

Upon examining the financial indexes, both gray and green hydrogen refueling projects have similar investment potential. Both projects yield an IRR of 13.72%, with an NVP of $5,054,833.47 for gray hydrogen, and $ 4,281,903.68 for green hydrogen, a difference of $700,000. These indexes are higher than those obtained for the hydrogen production sector, indicating that the refueling sector is a more profitable investment when considered in isolation. However, it is important to note that both sectors are integrated within the same facility and managed by a single entity, ensuring that the combined investment in both sectors is more attractive as a package.

3.6.4 Public transportation

In the proposed hydrogen value chain, both public and cargo transport are more sensitive to the origin of the energy used in hydrogen production, as it becomes a direct cost of the project. In both sectors, a comparison between gray and green hydrogen and diesel is made. Public transport, in particular, relies heavily on government subsidies, which are awarded based on distance traveled rather than the fare charged to users. This approach aims to incentivize more efficient service rather than cramming more passengers into each unit.

Figure 3.6 illustrates the accumulated income of the public transportation sector by comparing fuel sources. At the project's onset, internal combustion buses are cheaper than hydrogen units, resulting in a better starting condition. In addition, diesel, being a more cost-effective fuel, provides an advantage over hydrogen, assuming prices remain constant. However, hydrogen units have lower operating expenses, as reflected by the graph's closing gap between the lines. Both projects start at the same point when comparing hydrogen units since they have the same capital investment cost. However, the green hydrogen project quickly establishes a larger positive cash flow and accumulated income.

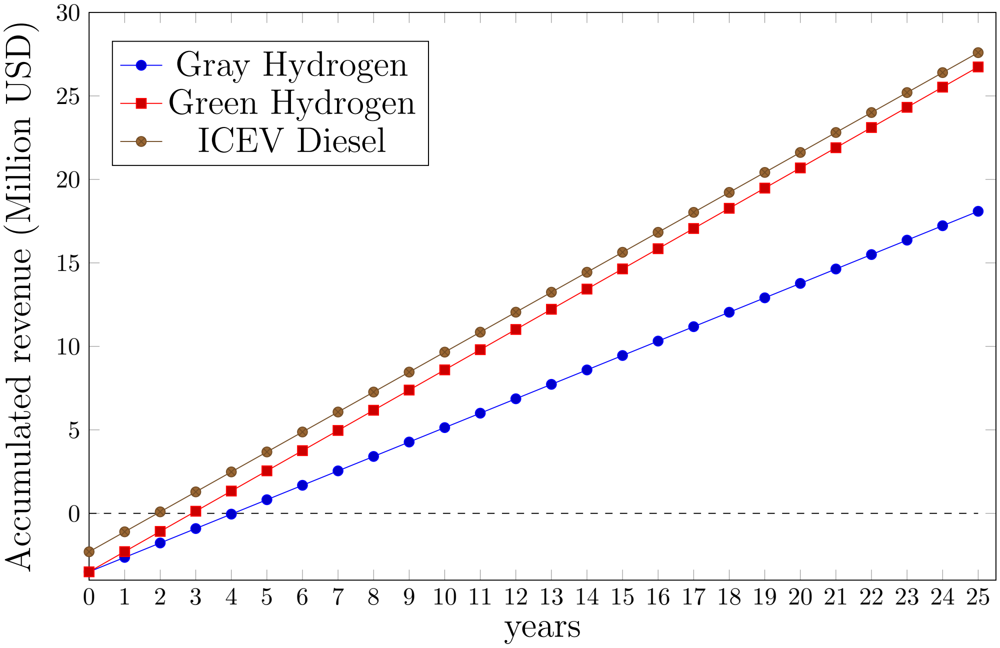


Figure 3.6: Cumulative revenue analysis, of the public transportation sector

Overall, the primary advantage of the diesel project lies in its capital investment and fuel cost. Green hydrogen public transportation is competitive within the evaluated timeframe despite the more expensive fuel. Moreover, if diesel prices were to increase, the green hydrogen project would eventually surpass the diesel project.

Table 3.8 displays the financial indicators for the public transportation sector of the project, demonstrating that, irrespective of the fuel type used, this sector represents an attractive investment opportunity. IRR for a diesel-powered public transportation project is higher by a margin, standing at 51.99%, compared to 34.53% and 24.57% for the green and gray hydrogen options, respectively.

Table 3.8: Financial analysis of the public transport sector

Financial analysis			
Project	IRR	NVP	Fuel price
Grid	24.57%	$3,629,232.84	$ 11.44
Solar	34.53%	$6,350,609.59	$ 7.55
Diesel	51.99%	$7,328,337.87	$ 1.36

However, when considering the NVP evaluation, the diesel project's advantage is reduced, as its projected NVP of $7,328,337.87 is less than a million dollars in difference from that of green hydrogen produced and refueled by solar power. The NVP indicates that diesel and green hydrogen are closer in comparison than what is suggested by IRR, with the primary difference being the capital investment. If fuel prices were to fluctuate or if the Mexican government were to stop subsidizing fossil fuels, making diesel more expensive, or if hydrogen units could be purchased more cheaply through subsidies or tax credits, then the IRR and NVP of the green hydrogen project could be improved. Nevertheless, as it stands, the public transportation sector powered by green hydrogen represents a viable investment opportunity.

3.6.5 Cargo transportation

The cargo transportation sector of the project lacks government support in the form of subsidies, which accentuates the difference in cash flow and makes it less of an income equalizer. Figure 3.7 illustrates the accumulated income of the evaluated projects. Notably, the green hydrogen-fueled project outperforms the diesel-fueled project by year 9, quickly overcoming the advantage of lower capital investment in internal combustion units. However, this is not the case for gray hydrogen, as its cost proves too challenging.

These findings suggest that, at present, hydrogen-fueled trucks could be a viable alternative to diesel units if hydrogen costs can be negotiated and fixed.

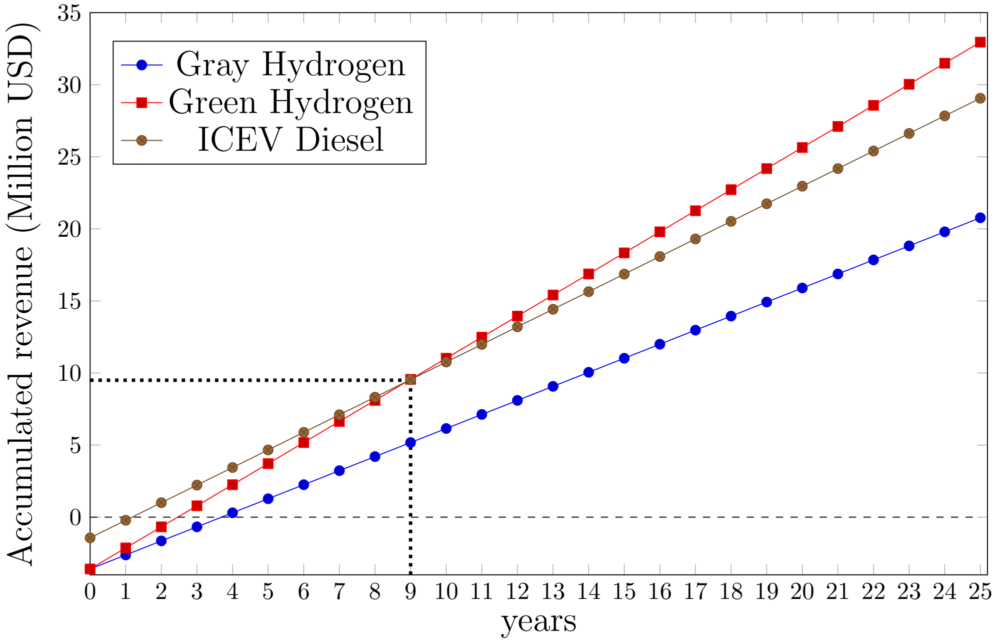


Figure 3.7: Cumulative revenue analysis, cargo transportation sector

The financial indexes for the cargo transportation sector of the project are presented in Table 3.9. The IRR of the diesel-fueled sector is superior to that of green and gray hydrogen, with a value of 85%. However, even with an IRR of 40.66%, green hydrogen still remains a great investment option considering the given factors. Nevertheless, as observed in the public transportation section, the NVP evaluation reduces the advantage of diesel, with a difference of less than fifty thousand dollars. This result can be attributed to the higher capital investment cost of the hydrogen units. Despite this, if conditions improve to acquire cheaper hydrogen units, a more attractive investment option that outshines diesel alternatives can emerge, given the higher accumulated income of hydrogen units within the evaluated time frame.

Table 3.9: Financial analysis of the cargo transport sector

Financial analysis			
Project	IRR	NVP	Fuel price
Grid	27.04%	$4,417,379.78	$ 11.44
Solar	40.66%	$8,251,554.20	$ 7.55
Diesel	85%	$ 8,300,254.52	$ 1.36

3.7 Energy and emission analysis

Energy and emissions are interdependent factors in transportation technologies, as the amount of energy required to operate a vehicle can affect the emissions produced. For FCB, the most pollutant project is the gray hydrogen fueled buses, followed by diesel and green hydrogen, as shown in table 3.10, furthermore, fuel cell buses have no emissions during operation, meaning that no emissions are produced close to the passengers.

Table 3.10: Emissions GHG of buses

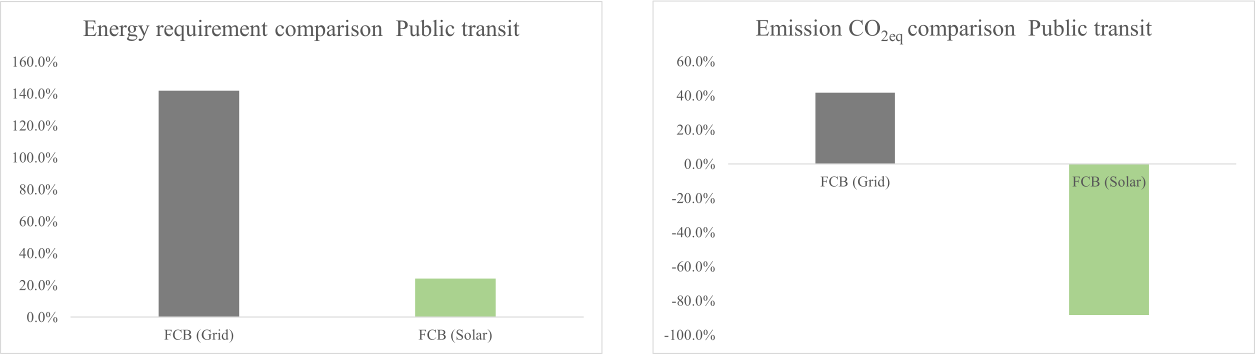
GHG Emissions(g/km)				
Project	WTP	OP	MMS	Total
ICEV (Diesel)	303.22	1535.96	23.57	1862.76
FCB (Grid)	2596.40	0	41.88	2638.29
FCB (Solar)	175.39	0	41.88	217.28

Fuel cell buses (FCBs) have similar energy requirements for operation and maintenance, but the hydrogen source can significantly impact on the well-to-pump phase. Hydrogen produced using the national grid is 3.5 times more energy-intensive than that from solar photovoltaic sources. In contrast, internal combustion engine vehicles (ICEVs) using diesel fuel are less energy intensive in the well-to-pump phase than hydrogen production but almost 14% more energy intensive during vehicle operation, energy requierement is shown in Table 3.11.

Table 3.11: Energy requirement of buses

Energy requirement (kj/km)				
Project	WTP	OP	MMS	Total
ICEV (Diesel)	2490.08	14148.30	634.53	17,272.92
FCB (Grid)	28956.96	12179.31	634.53	41,770.80
FCB (Solar)	8646.15	12179.31	634.53	21,460.00

Figures 3.8a and 3.8b depict the energy requirement and emissions of gray and green hydrogen, compared to the diesel public transport units, fuel cell vehicles are more energy intensive that ICEV, FCB fueled by hydrogen produced from the grid are 140% more energy intensive than diesel buses, while green hydrogen fueled FCBs are only 24% more compare to diesel buses. On the other hand, gray hydrogen fueled FCBs are 41% more pollutant than Diesel buses, while green hydrogen fueled FCBs have a reduction of 88% on emissions compared to Diesel buses.


Energy requirement comparison Public transit

Emission CO_{2eq} comparison Public transit

(a) Energy requirement comparison, public transportation units

(b) CO_2eq emission comparison, public transportation units

Figure 3.8: Energy and emissions analysis for public transport units

As for cargo vehicles, FCTs fueled by gray hydrogen pollutes the most, followed by diesel trucks and green hydrogen fueled FCTs, as shown in Table 3.12, neither FCTs emit pollutants during operation.

Table 3.12: Emissions GHG of cargo trucks

GHG Emissions(g/km)				
Project	WTP	OP	MMS	Total
ICEV (Diesel)	207	1054	0	1261
FCB (Grid)	1681	0	0	1681
FCB (Solar)	113	0	0	113

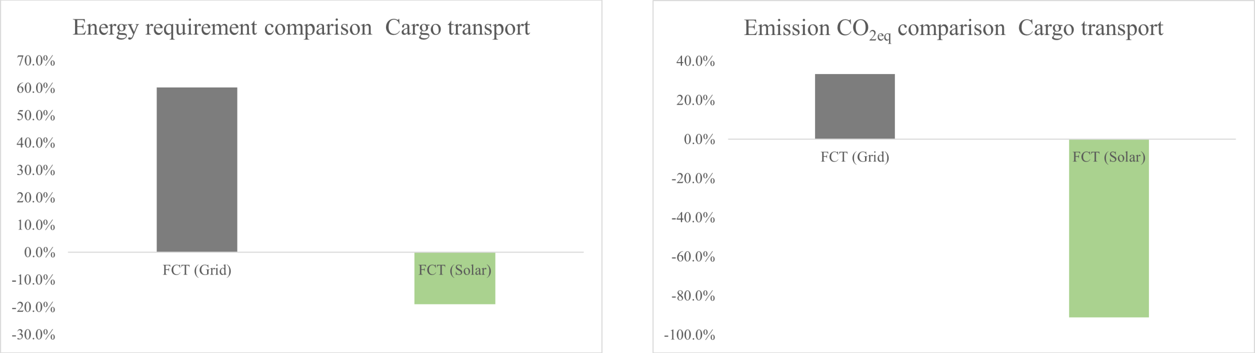
Contrary to FCBs, green hydrogen fueled trucks are the least energy intensive option for cargo trucks, still gray hydrogen trucks are the most energy intensive. Both FCTs are less energy intensive on the operating phase, at the same time, they are more intensive at the well to pump phase, which means that hydrogen production is more energy intensive, as shown in Table 3.13, the results of Tables 3.10, 3.11, 3.12, 3.13 are shown in Appendix 1 as graphs, making easier to compare the results.

Table 3.13: Energy requirement of cargo trucks

Energy requirement (kj/km)				
Project	WTP	OP	MMS	Total
ICEV (Diesel)	2490.08	14148.30	0	16638.39
FCB (Grid)	18755.91	7889.1008	0	26645.01
FCB (Solar)	5600.5152	7889.1008	0	13489.62

Figure 3.9a shows the energy requirement of FCTs compared to diesel fueled trucks, gray hydrogen FCTs are 60% more energy intensive than diesel trucks, while green hydrogen FCTs, present a reduction of 19% in energy requirement. As for emissions, FCTs using hydrogen produced from the electrical grid, are 33% more pollutant than ICEVs, FCTs fueled by green hydrogen have a reduction of 91% on emissions compared to ICEVs.

Results show consistently that evaluating the energy requirement, emissions, and financial indexes, FCVs could have an advantage compared to IVECs; this edge is only realized fully for the green hydrogen-powered sections of the project, as such FCVs rely heavily on the fuel source and cost for the evaluation of the parameters chosen.



(a) Energy requirement comparison, cargo transportation units

(b) CO_2eq emission comparison, cargo transportation units

Figure 3.9: Energy and emissions analysis for cargo transportation units

3.8 Social impact

The emissions were converted into monetary terms using the CO_2 equivalent approach to evaluate the social impact. This approach was chosen because it allows for a direct comparison of the environmental impact of different technologies. For the public transportation section, shown in Table 3.14, the social impact of green hydrogen-fueled buses was estimated to be the least negative, with an annual cost of $52,677, while gray hydrogen-fueled buses would cost up to $639,610 to society.

In comparison, diesel-fueled transportation would cost $451,596 and also has the disadvantage of producing tailpipe emissions, this means that green hydrogen fueled FCBs have a societal impact reduction of 88% compared to diesel buses.

Table 3.14: Social impact of public transport

Social impact evaluation		
Project	Emissions (tCO_2)	Social cost
ICEV (Diesel)	3671.51	$451,596.29
FCT (Grid)	5200.09	$639,610.86
FCT (Solar)	428.27	$52,677.30

The societal impact of cargo transport of Jet A1 fuel from Merida to Cancun is presented in Table 3.15. As with the public transportation evaluation, green hydrogen from solar energy has the lowest impact, with a cost of $15,371.60, while diesel and gray hydrogen have an impact of $171,536.16 and $228,669.54 respectively. This finding highlights the adverse scenario for hydrogen-fueled vehicles created by the current composition of the national grid, while FCTs fueled, green hydrogen fueled trucks have a reduction of 91% on impacts on society as accounted by its financial equivalent.

Table 3.15: Social impact of cargo transport

Social impact evaluation		
Project	Emissions (tCO_2)	Social cost
ICEV (Diesel)	1,394.60	\$171,536.16
FCT (Grid)	1,859.10	\$228,669.54
FCT (Solar)	124.97	\$15,371.60

Overall, the social impact evaluation underscores the importance of considering the environmental impact of transportation technologies in economic terms. By comparing the cost of different technologies, decision-makers can make informed choices considering economic and environmental factors. It also highlights the potential of green hydrogen as a promising technology for reducing the negative impact of transportation on society. However, further investment is needed to develop the infrastructure necessary to support the deployment of green hydrogen-fueled vehicles.

CONCLUSIONS

The proposed value chain for hydrogen has been evaluated, demonstrating that using green hydrogen for public transportation in Merida and cargo transportation of fuel is a feasible and competitive alternative to diesel. The project includes a fleet of 5 fuel cell buses and 10 fuel cell trucks, requiring a daily hydrogen demand of 1109 kilograms and 11,090 liters of deionized water. The project also entails an annual energy consumption of 25,703,823 kWh, being supplied by a 16500 kW photovoltaic power plant that produces over 26,000,000 kWh per year.

The refueling station, costing 8.2 million dollars, is the biggest investment of the project, followed by the photovoltaic power plant at 5.7 million USD and the bus and truck fleets at 3.5 million USD each. Financial analysis confirms the feasibility of every project section, with a clear increase in value as time passes, and the cargo transportation sector in the Merida-Cancun corridor being the most profitable, while the photovoltaic power plant energy production is the least profitable. It is crucial to produce green hydrogen using renewable energy sources, such as the proposed photovoltaic project, to compete with diesel and fuel prices must be stabilized through long-term contracts. Although fossil fuels are subject to a volatile worldwide marketplace, subsidies from the Mexican government are helping mitigate this risk, giving an advantage to ICEVs compared to FCVs.

In conclusion, using green hydrogen in public transportation is a viable alternative to diesel, with incentives like tax credits, exceptions, and emissions trade making it even more attractive. The transportation of goods using green hydrogen may already be a superior alternative to diesel due to lower running costs but higher capital costs, depending on hydrogen supply capability. The results of this study provide valuable insight into future alternative transportation projects, particularly in Merida, and similar studies in different cities could develop. Future research should continue to compare fossil fuels, hydrogen, and battery electric vehicles using updated data to test the capacity of alternative technologies in different market niches, as well as different cities and metropolitan areas.

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APPENDIX A

Appendix A contains the results of Energy requirement and emissions of the technologies evaluated, in detail the stages divided.

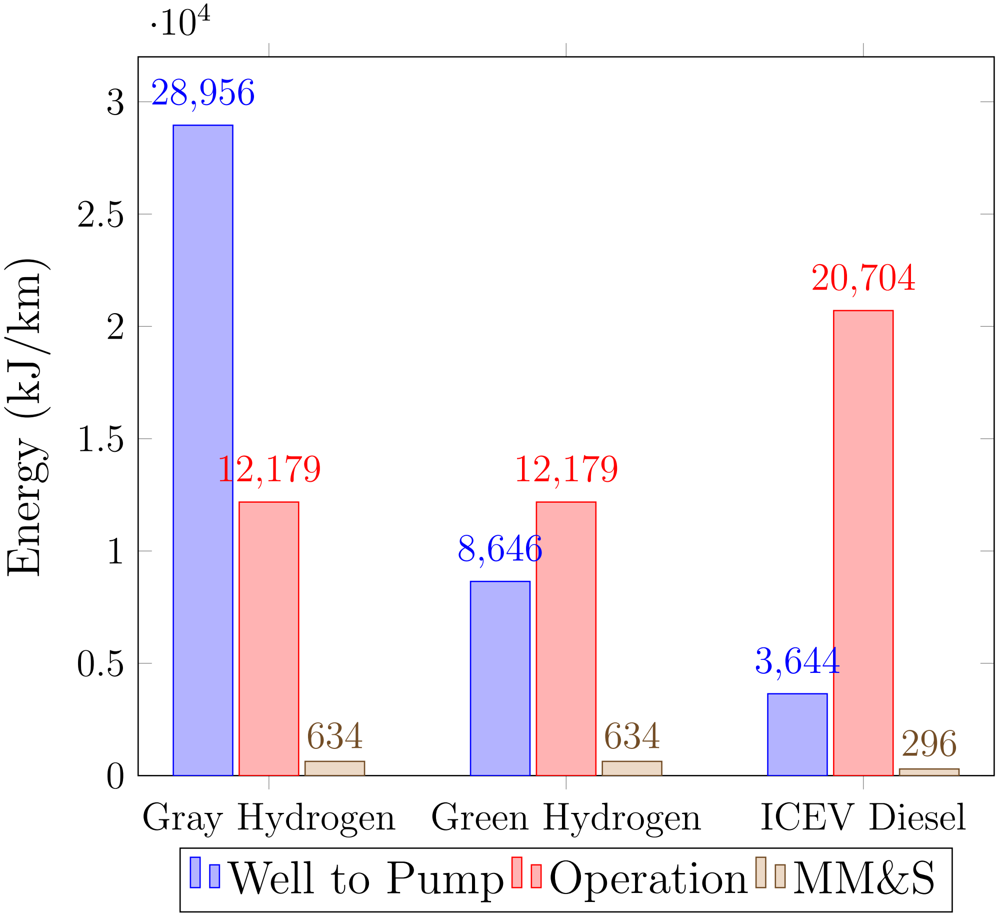

Figure 10: Energy requirement, public transport

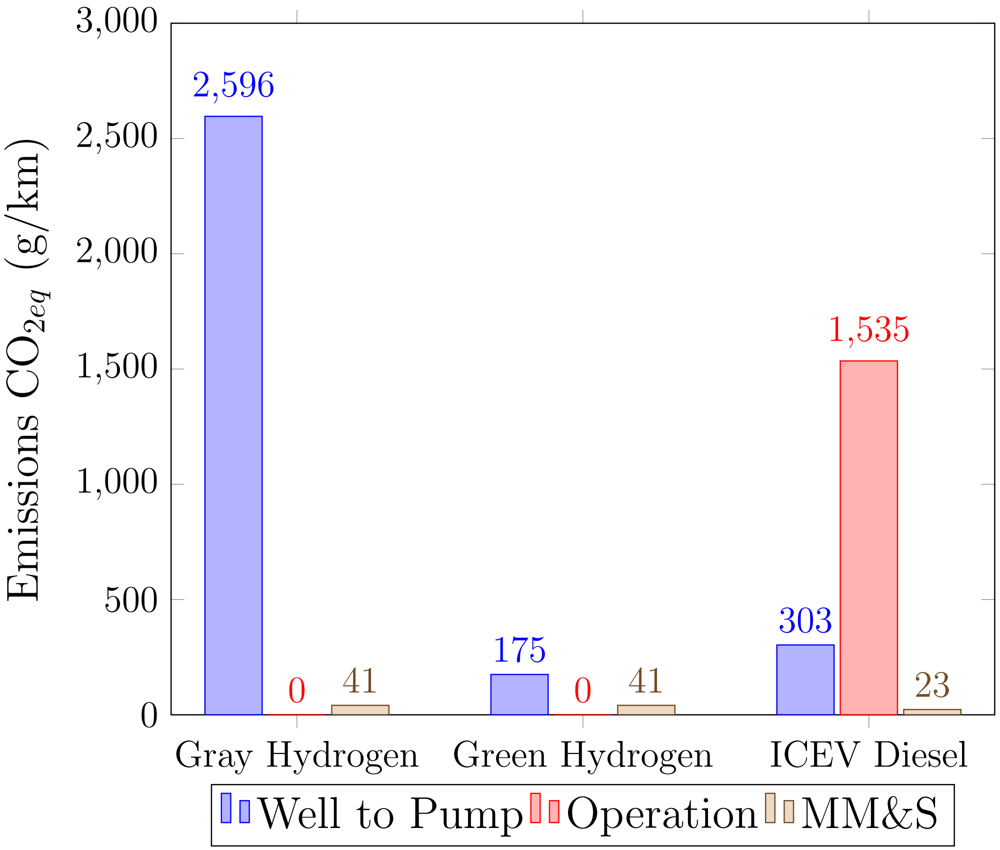

Figure 11: Emissions, public transport

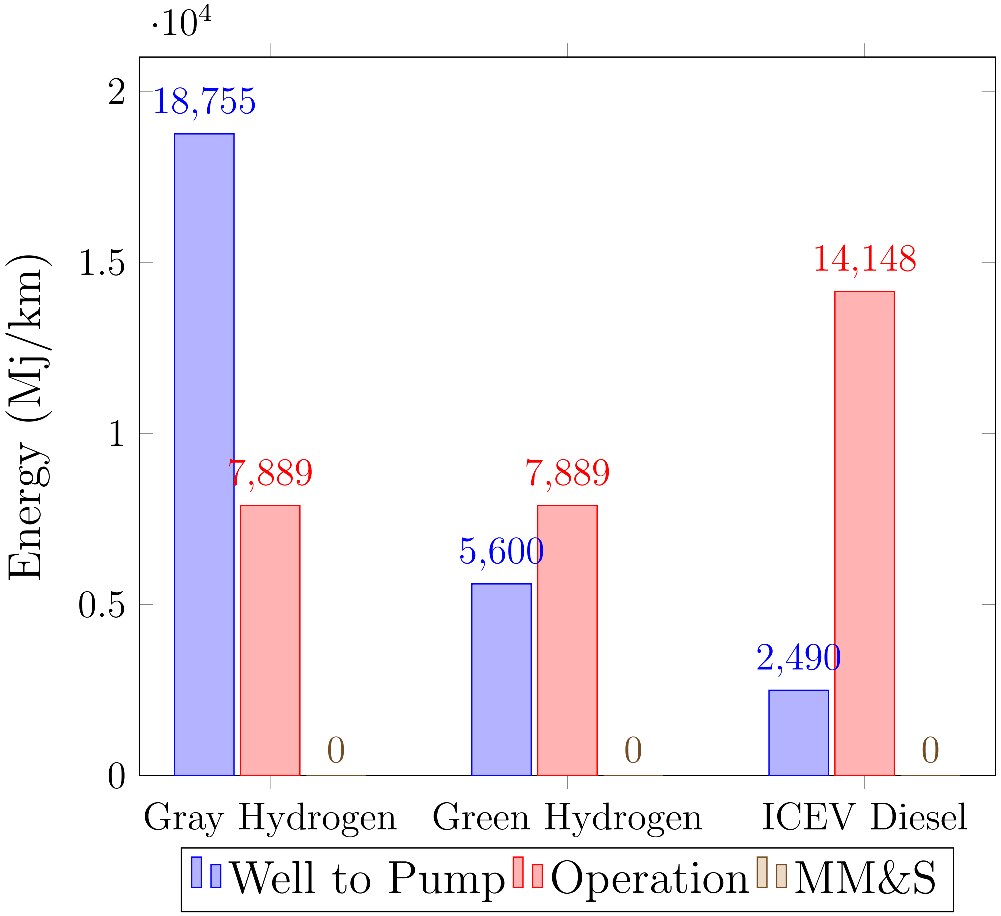

Figure 12: Energy requirement, cargo transport

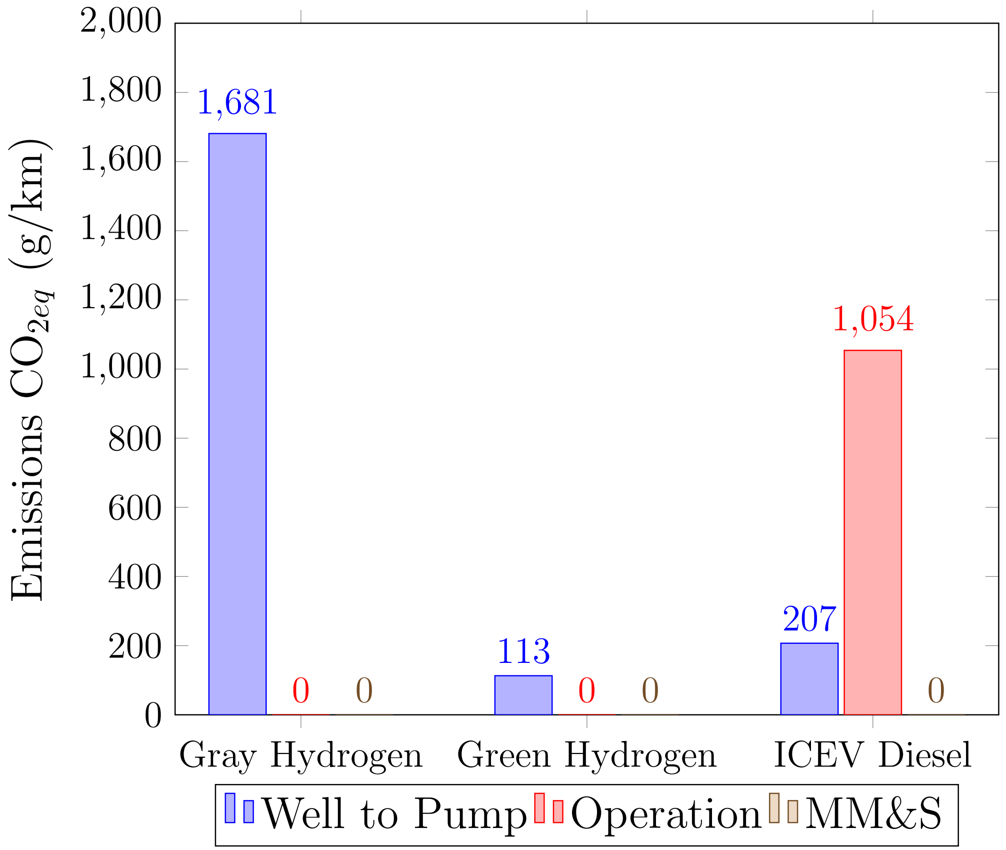

Figure 13: Emissions, cargo transport