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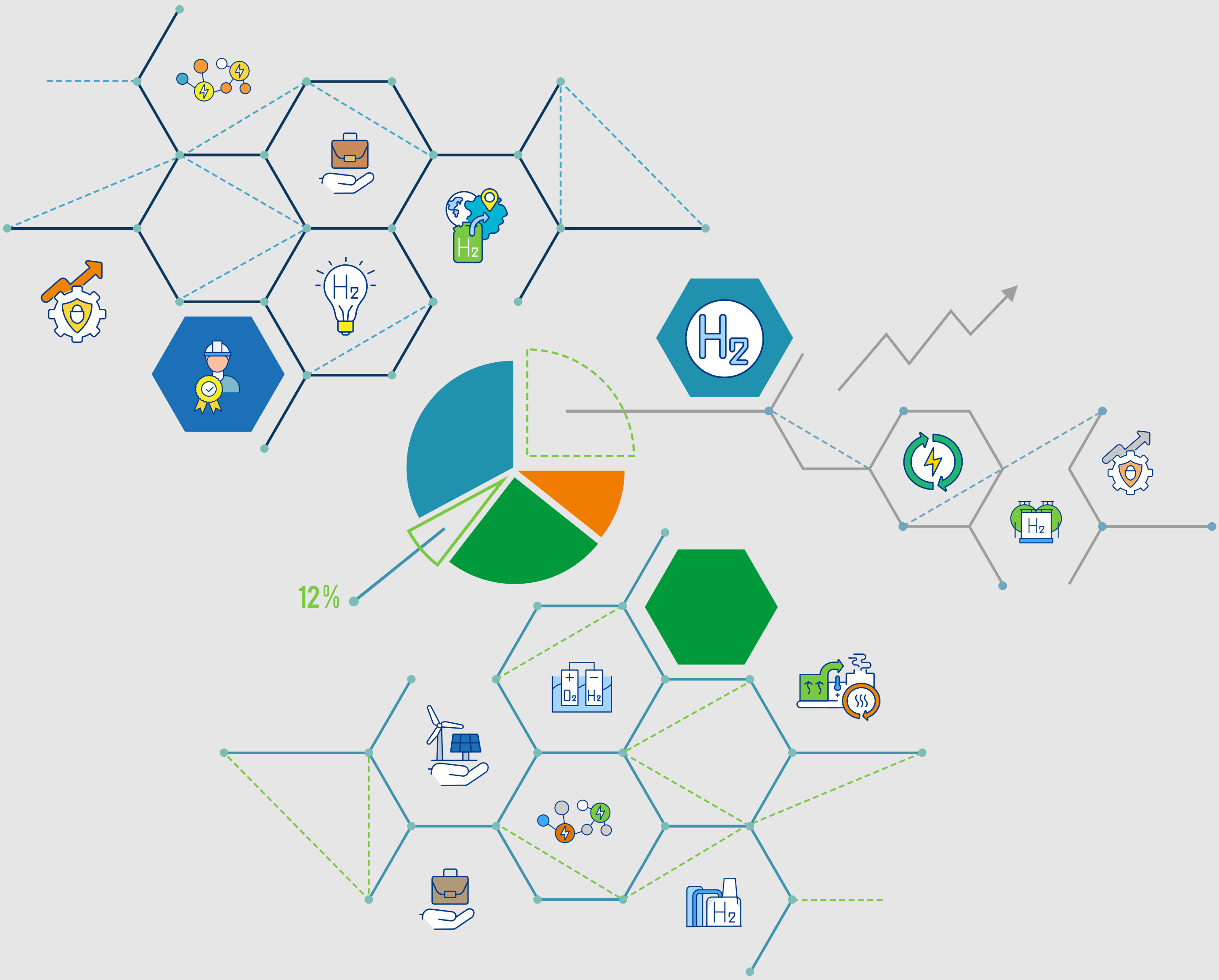
Green Hydrogen in Mexico: towards a decarbonization of the economy

Volume VII: Results Integration and General Recommendations



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Abbreviations

BAU	Business-as-Usual
BEV	Battery Electric Vehicle
CAEX	Mining haul trucks, from Camiones de Extracción in Spanish
CAPEX	Capital Expenditures
CCGT	Combined Cycle Gas Turbine
CFE	Comisión Federal de Electricidad
CO_2E	CO_2 equivalent GHG emissions
EZ	Electrolyzer
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas emissions
H_2	Hydrogen
H_2B	Hydrogen Breakthrough Scenario
H35	Gaseous hydrogen compressed to 350 bar, supplied at HRS
HRS	Hydrogen Refueling Station
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
INECC	National Institute of Ecology and Climate Change
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Hydrogen
MW	Megawatt
$MTCO_2E$	Million tons of CO_2e
NDC	NDC Compliance Scenario
NDCs	Nationally Determined Contributions
PEMEX	Petróleos Mexicanos
PV	Solar photovoltaic
SENER	Secretaría de Energía, Ministry of Energy
SMR	Steam Methane Reforming (H_2 production)

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Executive Summary

Green H_2 is produced by splitting water into hydrogen oxygen through electrolysis. When supplied with renewable energy, it can provide a zero-carbon alternative that is independent from fossil resources, avoiding supply and price volatility.

The advent of the green hydrogen economy could set the ground for new business opportunities for public and private companies as a key vector for decarbonization with major applications in energy, mobility, and industry to help Mexico comply with climate goals while creating new jobs and business opportunities.

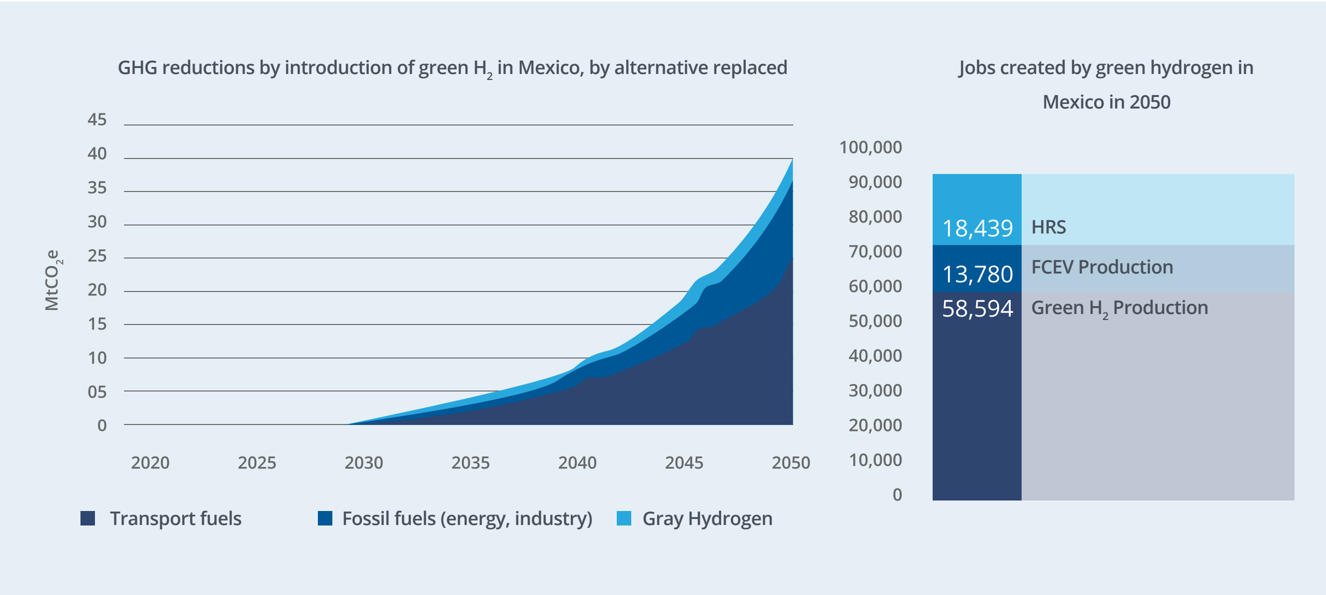
In Mexico, if given the right policy support and favorable conditions for industry adoption, over 670 MW of electrolysis could be deployed by 2030. In 2050 the national electrolysis capacity could reach 38.7 GW driven by 15.5 billion USD of investments since the late 2020's and creating a Mexican green hydrogen market valued at 5.7 USD billion per year.

Overall, nearly 300 $MtCO_2e$ could be avoided by introducing green hydrogen in Mexico by 2050.

Two-thirds of the emissions reduction correspond to replacing fossil fuels in fuel cell electric vehicles (FCEV) for public and freight transport. By 2050 the introduction of green hydrogen technologies could reduce over 40 $MtCO_2$ of emissions every year, by up to 26.7 $MtCO_2e$ in the transport sector, 3.2 $MtCO_2e$ in the operations of PEMEX, and up to 7.6 $MtCO_2e$ in energy storage, thermal uses, and other industrial applications.

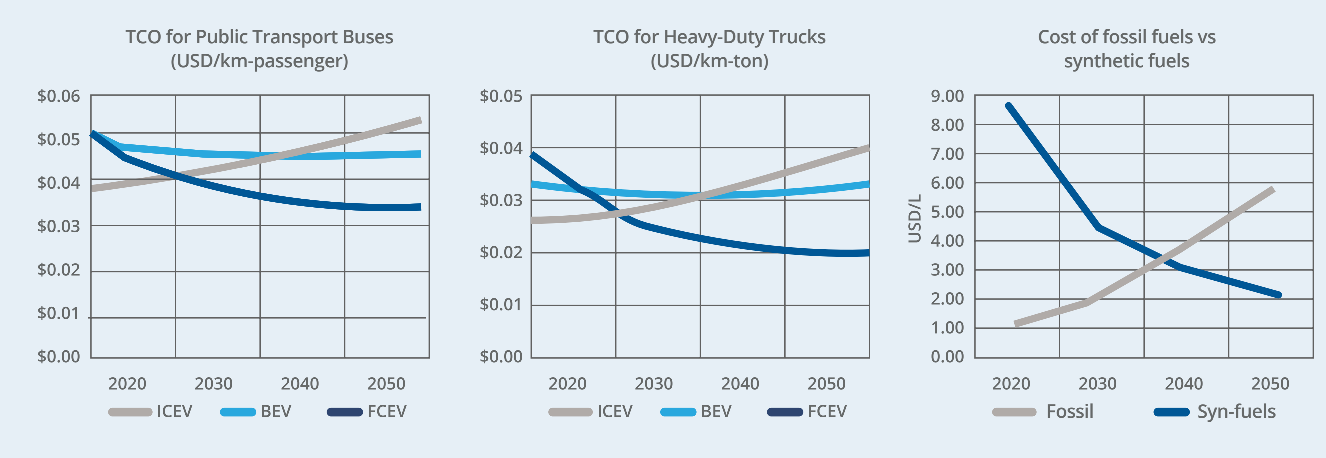
Green hydrogen can also be a driver of job creation and by mid-century 90,000 people in Mexico could work in green H_2 infrastructure and the production of heavy-duty FCEVs, with 67% of jobs created in the production of hydrogen, 20% in green hydrogen refueling stations (HRS), and the remaining 13% in the hydrogen FCEV automotive industry.

Figure 1. GHG emissions reductions and jobs created by green hydrogen in Mexico.



Mexico will have the potential to install up to 22 TW of electrolysis capacity across its territory to produce green hydrogen at an average cost of 1.4 USD/kg in 2050, powered mostly by PV generation. The main driver for the adoption of green hydrogen will be its cost competitiveness, projected to be achieved in Mexico for most applications around 2040 or 2050, depending on the level of government support, industry adoption, and global cost reduction of hydrogen technologies. Average levelized costs of hydrogen (LCOH) in Mexico will be as low as 2.55 USD/kg in 2030 and 1.22 USD/kg in 2050.

Figure 2. TCO curves[1] for diesel, battery electric, and FCEV for public transport buses (left), heavy-duty freight trucks (center), and cost of diesel vs. synthetic fuels (right).



The segment which presents the largest business opportunities is road transport, among the first in which green hydrogen will reach cost competitiveness with public transport buses and freight trucks being cheaper than both conventional internal combustion engine vehicles (ICEV) and battery electric vehicles (BEV) on a total cost of ownership (TCO) basis before 2030, which will boost early adoption.

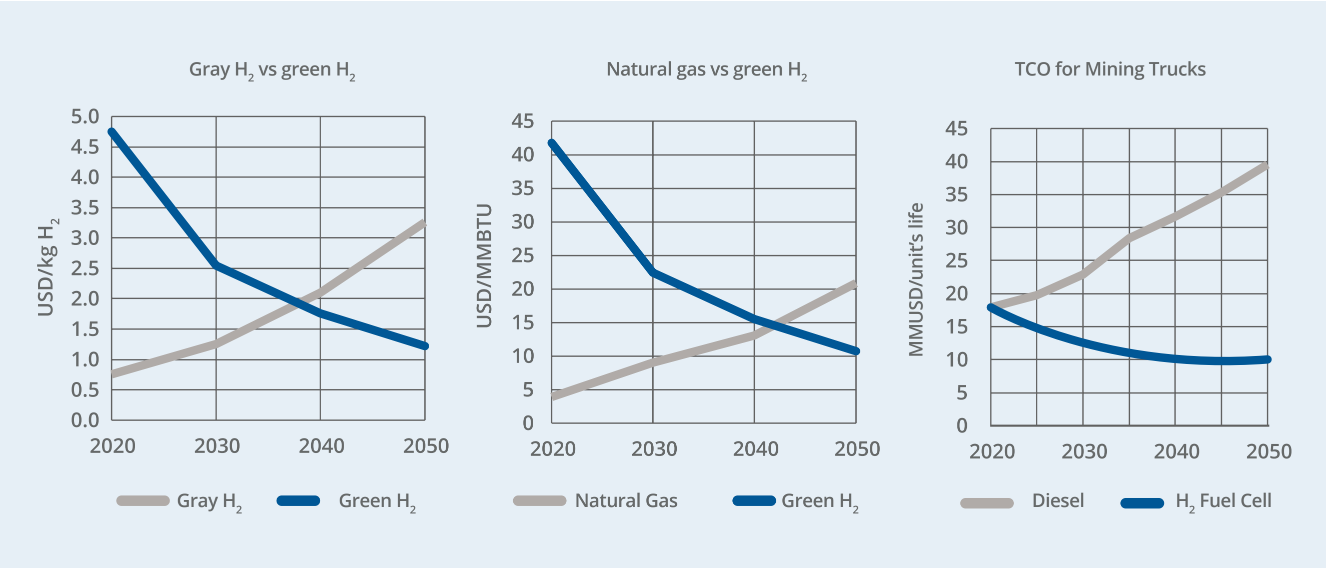
By 2050, up to half a million heavy-duty FCEVs could be on the roads in Mexico, with around 50% in public transport and 50% in long-haul freight. In 2050, selling green hydrogen instead of fossil fuels at HRS for these FCEVs would be an opportunity worth 6 billion USD per year, reducing 22 $MtCO_2e$/year of GHG emissions and will have enabled the deployment of 19.4 GW of electrolysis capacity. To get there, by 2030 more than 3 thousand FCEVs should be on the roads supplied by 150 MW of electrolysis and in 2040 the green H_2 demand for public buses alone would be the same as the total hydrogen demand of PEMEX in 2020.

Synthetic fuels will be next in reaching cost parity as early as 2035 to power the aviation industry with carbon neutral fuels. These synthetic hydrocarbons produced by combining green H_2 with captured CO_2 could substitute roughly 9,200 barrels of oil equivalent per year by 2050, supplying 12% of aviation's fuel demand, and contributing to one third of the transport sector's emissions reduction targets as set in Mexico's NDC. For this application alone, 3,500 MW of electrolysis capacity would be required by 2050.

The largest area of opportunity for green hydrogen in industry is in the mining sector, with a demand that could reach half a million tons per year by 2050. Of this green H_2 demand, 50% would power 1,500 fuel cell mining trucks, 42% would be used to reduce one quarter of the country's iron ore for steel making, and 8% to supply 4.3 PJ of energy for the mining industry's thermal applications. Together they would account for over 80% of the non-transport private sector demand by 2050.

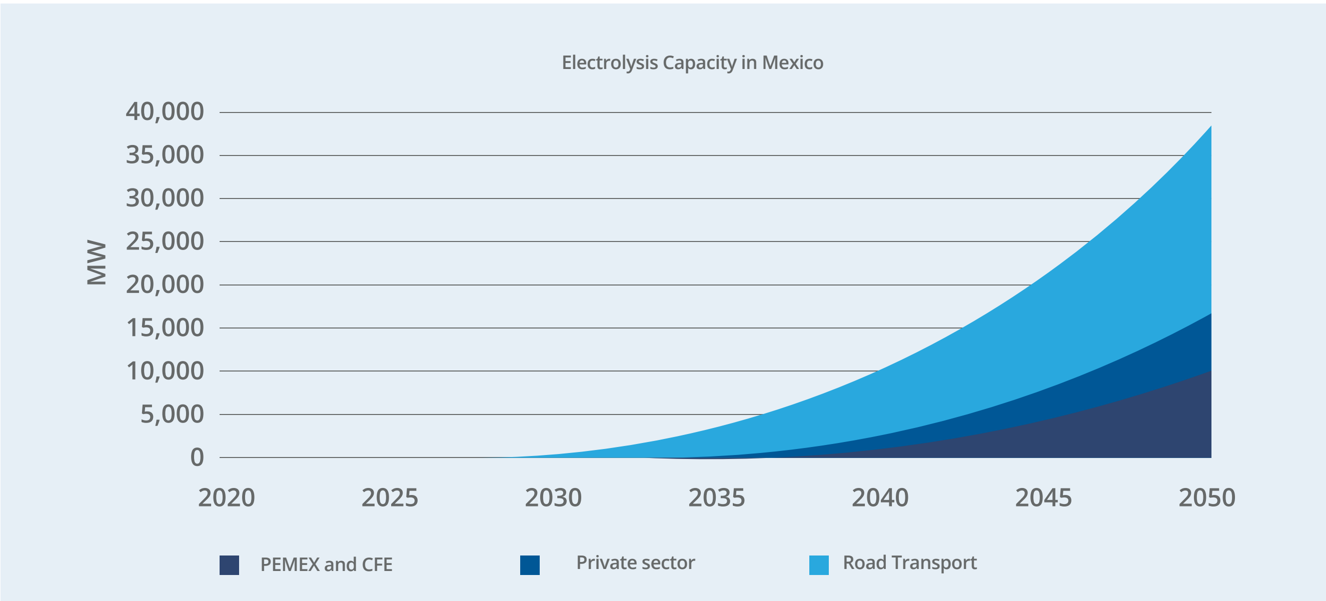
[1] The TCO calculations consider travel of 65,000 km/year for public transport buses and 160,000 km/year for heavy-duty freight trucks for all technologies.

Figure 3. Cost curves of hydrogen vs green hydrogen (left), natural gas vs green hydrogen (center), and TCO of diesel and H_2 FCEV mining trucks (right)



Even before 2030, PEMEX and CFE could lay the foundations for the development of a large-scale green hydrogen sector in Mexico with over 11GW of potential electrolysis by 2050 and a green H_2 market of 1.2 billion USD per year, contributing to its energy sovereignty with a fully locally produced and carbon-free supply. By 2050, PEMEX could produce every year nearly 1.4 million tons of green ammonia to make fertilizers every year and refine over 750 thousand barrels of oil per day using green hydrogen.

Figure 4. Projected electrolysis capacity deployment in Mexico.

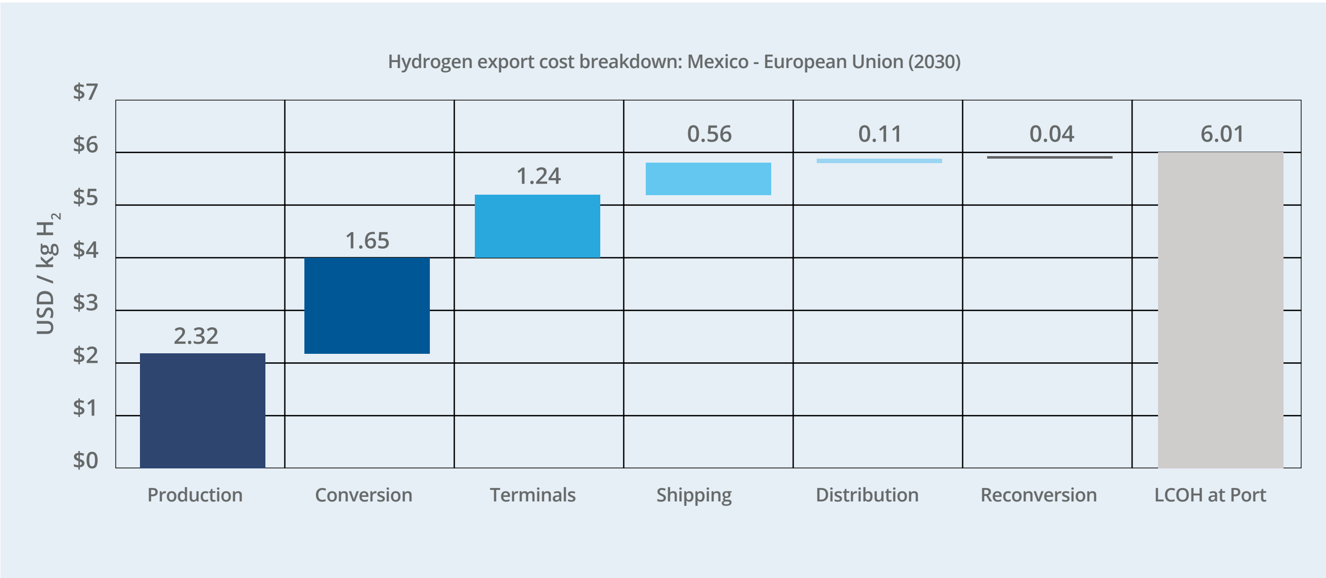


In the national electric system, green hydrogen energy storage would allow for an increase in renewable energy generation of 2% by 2050, and CFE could fuel 670 MW of thermal power plants using green hydrogen in an amount comparable to the total hydrogen demand of PEMEX in 2018. A blend of natural gas with hydrogen could be injected in the natural gas network but limited to small amounts in specific regions of the country with good renewable resources and a strong incentive to decarbonize given its a low economic competitiveness, representing under 460 MW of electrolysis in 2050.

Thermal applications in the chemical industry and cement manufacture will present a moderate green H_2 demand requiring 520 MW and 400 MW of electrolysis, respectively, and jointly replacing up to 350 billion cubic feet of natural gas per year by 2050. Opportunities as a chemical feedstock for flat glass, synthetic resins, and margarines will be minor relative to the total national green hydrogen market, where even a full replacement with green hydrogen supply would only demand 3,500 ton/year by 2050.

Mexico also has the potential to become a strong exporter of green hydrogen. As early as 2030 more than 300 million USD of green H_2 could be exported overseas. When compared to potential large exporters of green hydrogen, Mexico is placed as a competitive long-distance exporter to Europe and Asian markets, given a low projected green H_2 production cost enabled by good renewable resources and its privileged geographic position next to the US and with access to both the Atlantic and the Pacific oceans at a northern latitude, allowing it to compete closely with Chile and Australia. In 2030, Mexican green H_2 could be delivered in Europe at roughly 6 USD/kg and by pipeline to bordering US states at 2.5 USD/kg.

Figure 5. Hydrogen export breakdown by cost components from Mexico to the EU in 2030.



Additionally, hydrogen could boost the development of new industries in the country. Mexico has the potential to position itself as a leading manufacturer of FCEVs and to be competitive in the manufacture of H_2 power turbines, transport, and storage equipment.

To reach this potential, the country has already developed many intellectual, financial, and legal capabilities. However, Mexico should rethink its climate policy, promote renewable energies from political and regulatory standpoints, develop a National Hydrogen Strategy with defined targets and actions, and allocate funding and incentives for the development and adoption of green hydrogen infrastructure and technologies.

These measures could allow green H_2 to become cost-competitive up to a decade earlier and enable an accelerated deployment as early as the 2030's, allowing Mexico to join the global green hydrogen race as a strong player in the region.

1. Introduction

Green hydrogen can provide opportunities for companies in the public and private sectors to adopt with major applications in transport, energy, and as a feedstock for industry. Governments and companies worldwide see green hydrogen as a key vector for the decarbonization of a wide array of processes to comply with ambitious climate goals and the advent of the hydrogen economy is expected to set the ground new business opportunities and value creation at a global scale and in Mexico.

With a fortunate geography, a dynamic industrial ecosystem, and an evolving energy landscape, green hydrogen infrastructure could realistically grow in Mexico by mid-century to employ 90 thousand workers, reduce around 27 MtCO2e of GHG emissions per year, and represent an annual demand market of 5.7 billion USD, reaching close to 39 GW of installed electrolysis capacity for its development.

This report summarizes the findings from a series of studies which constitute a "Green Hydrogen in Mexico: towards an economy decarbonization", analyzing green hydrogen opportunities across multiple applications in the country, with opportunities for PEMEX (refining, production of ammonia, and synthetic fuels) and CFE (green H2 in gas turbines and injection in the gas network), opportunities for the private sector (mining, cement, and the chemical industry), in heavy-duty road transport (public buses and long-haul trucks), the potential to export green hydrogen, and the impacts in the country of developing its value chain in job creation, market potential , GHG emissions reduction, and the manufacture of hydrogen technologies.

For most end-uses two realistic scenarios have been developed. 'NDC Compliance' (NDC) assumes Mexico will fulfill its climate commitments to comply with the Paris Agreement according to its Nationally Determined Contributions (NDCs) but not going beyond in climate or environmental action. 'Hydrogen Breakthrough'(H_2B) makes more optimistic assumptions with high industry adoption, sharper decline in costs and intensive policy support worldwide and in Mexico, following the projections of the Hydrogen Council. Unless stated otherwise, the results shown in this report correspond to the Hydrogen Breakthrough scenario to highlight the country's green hydrogen potential and its impacts.

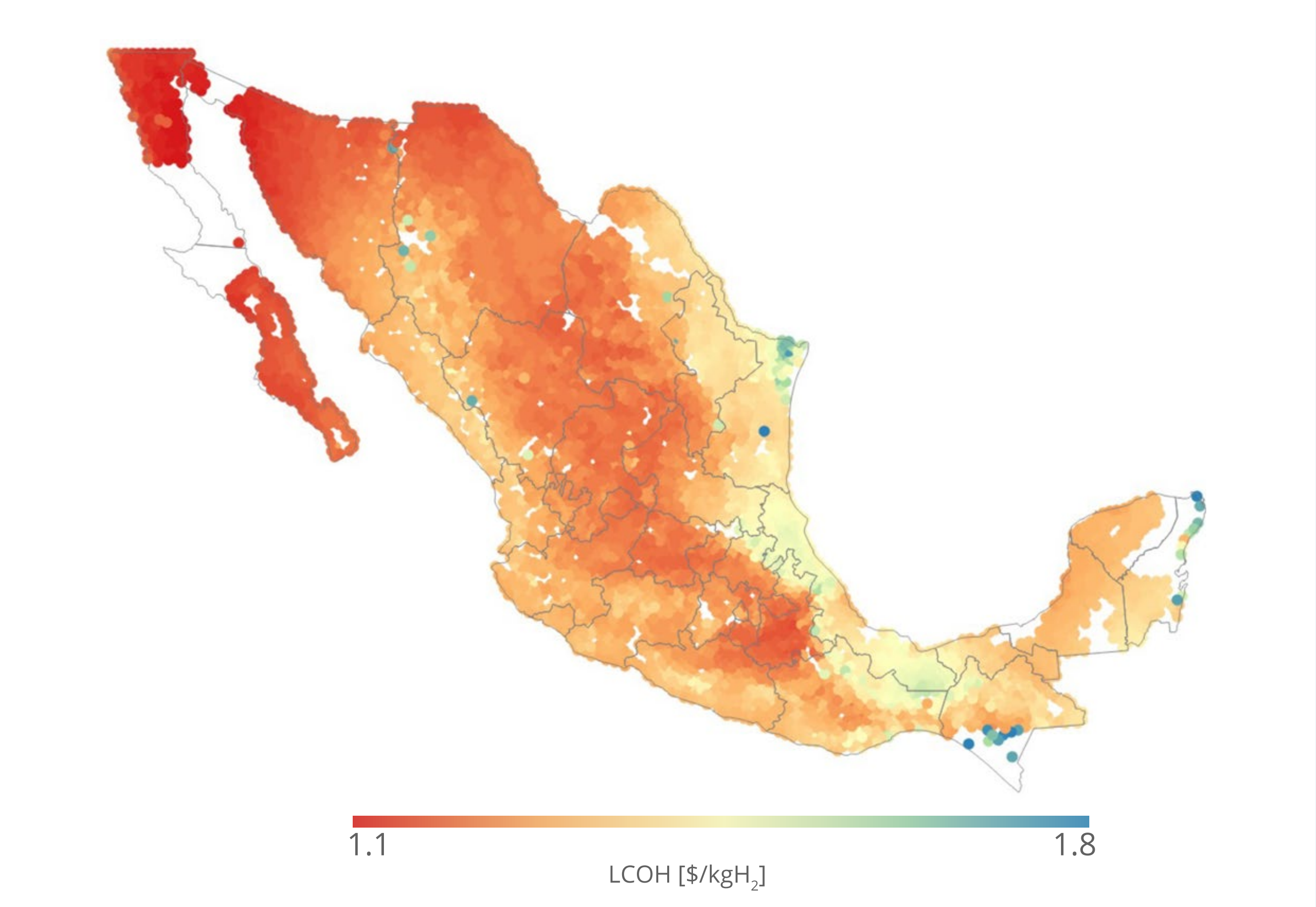
Mexico: a country with high potential to produce green hydrogen

Green hydrogen is produced by the electrolysis of water, a process which splits the H_2O molecule with electricity to separate the hydrogen and the oxygen. Unlike conventional fossil-based gray hydrogen, which is produced mainly from steam reforming processes (SMR) of natural gas or from coal gasification, green hydrogen provides a low carbon fuel, energy carrier, or chemical feedstock which can be produced locally and is independent from fossil resources, avoiding supply constraints and price volatility. This enables new major uses of hydrogen in renewable energy storage, electric mobility, green chemicals, decarbonization of natural gas, liquid synthetic fuels, renewable gases, and heat and power for buildings and industry.

In Mexico, the existing hydrogen market consumed more than 220,000 tons/year in 2020, of which 98.6% is captive and in the hands of PEMEX. The production of merchant hydrogen in Mexico is approximately 2,650 tons per year, most of which is provided by Air Liquide, Linde, and Cryo-Infra. There is a small international hydrogen trade balance in Mexico of under 750 tons/year led by private transactions.

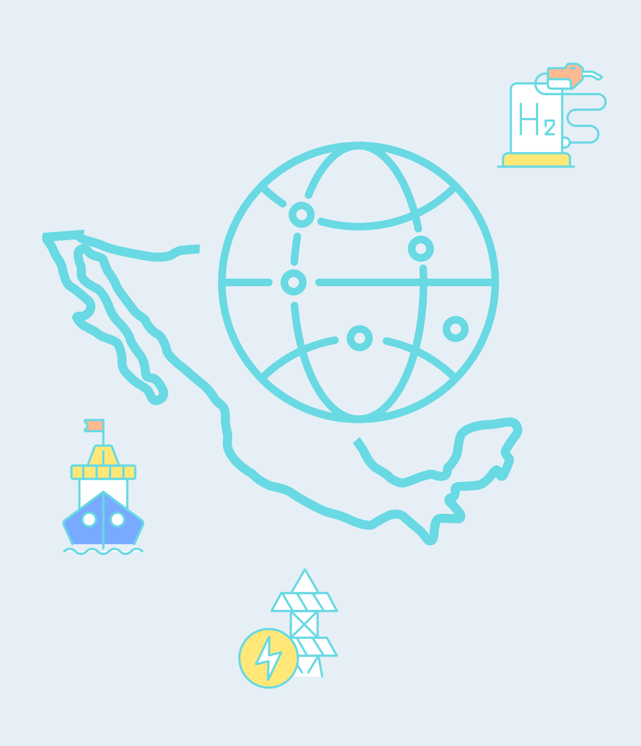
Furthermore, Mexico is in a privileged position to become a leader in the development of green hydrogen since the country has a well-distributed renewable energy potential and a well-developed energy infrastructure that could effectively enable green hydrogen developments. Additionally, Mexican universities and research centers have been working on hydrogen technologies since the 1990s.

Figure 1-1. LCOH from hybrid wind-solar PV production in Mexico in 2050.



Mexico has the geographic potential to install up to 22 TW of electrolysis capacity across the country to produce green H_2 at an average levelized cost of hydrogen (LCOH) in 2050 of 1.4 USD/kg, powered mainly by PV generation.

The main driver for the adoption of green hydrogen will be its cost competitiveness, projected to be achieved for most applications around 2040 or 2050, depending on the level of government support, industry adoption, and global cost reduction of hydrogen technologies with average projected LCOH in Mexico as low as 2.55 USD/kg in 2030 and 1.22 USD/kg in 2050.

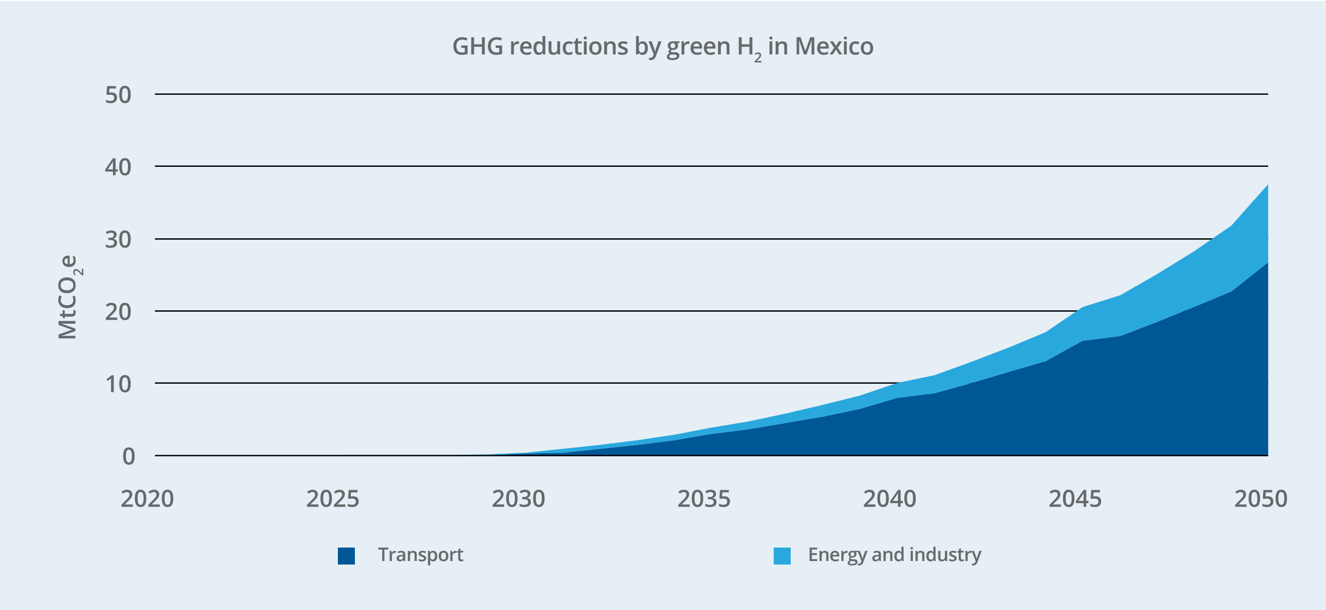


2. Potential Impacts of Green Hydrogen in Mexico

Environmental Impact: 300 MtCO_2e of cumulative reductions by 2050.

In 2050, the introduction of green H_2 technologies in Mexico could reduce emissions by up to 26.7 MtCO_2e/year in heavy-duty road transport, 3.2 MtCO_2e/year in the operations of PEMEX, and up to 7.6 MtCO_2e/year in energy storage, thermal uses, and other industrial applications. Overall, 40 MtCO_2e/year could be avoided in 2050, equivalent to 8.4% of the country's emissions in 2018. By mid-century, 300 MtCO_2e of cumulative emissions could be reduced by green H_2 in Mexico, of which two-thirds correspond to replacing fossil fuels by hydrogen in fuel cell electric vehicles for public and freight transport.

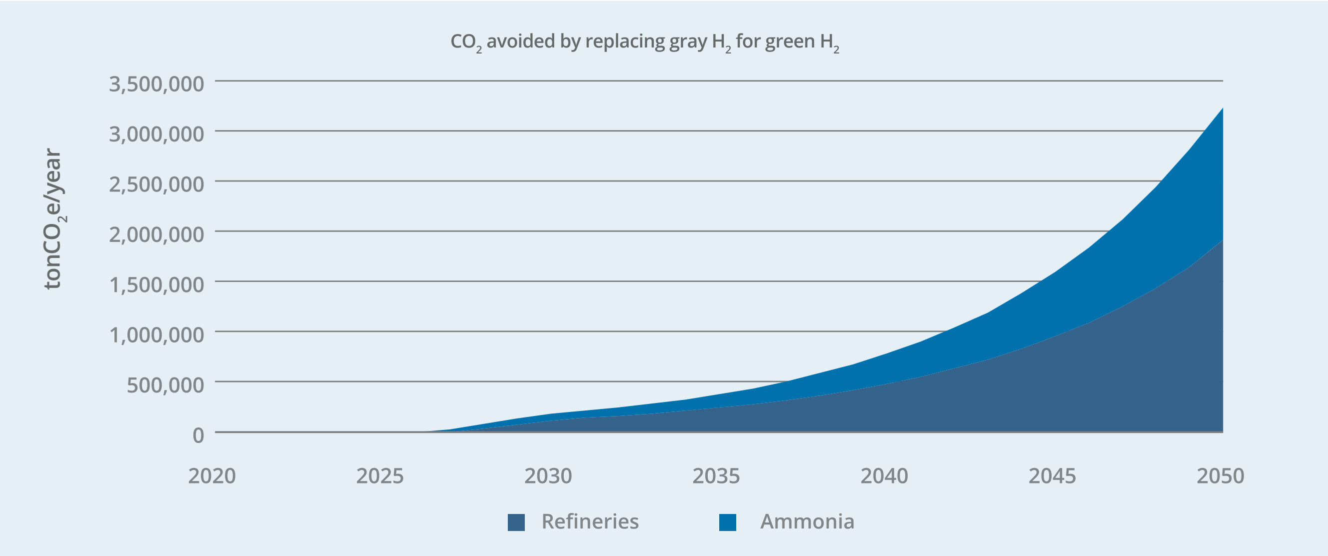
Figure 2-1. GHG emissions reductions from introducing green hydrogen in Mexico.



The green hydrogen end-uses can be divided into the replacement of gray hydrogen, replacement of fossil fuels, and liquid transport fuels. The environmental impact is calculated with the greenhouse gas (GHG) emissions that could be avoided by replacing conventional technologies such as fossil fuels or hydrogen from steam methane reforming, in million tons of carbon dioxide equivalent (MtCO_2e).

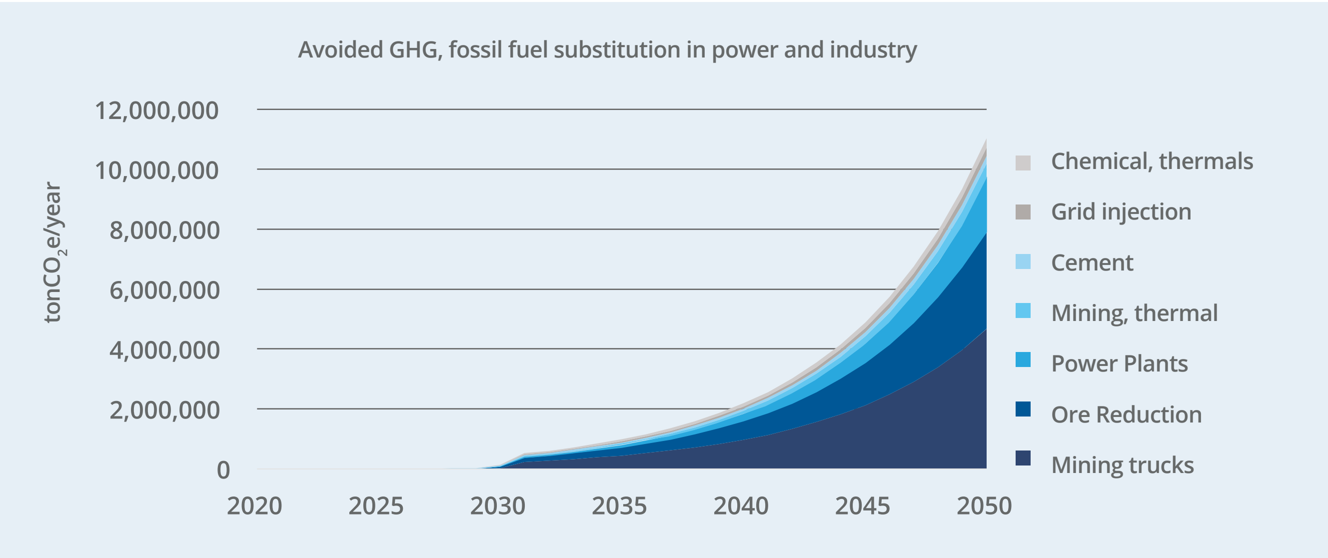
The CO_2 avoided by the introduction of green hydrogen by PEMEX in refineries and ammonia production in Mexico would surpass 180 ktCO_2e/year by 2030 and reach more than 3.2 MtonCO_2e/year by 2050.

Figure 2-2. Projected GHG emissions avoided by the replacement of gray H_2 with green H_2.



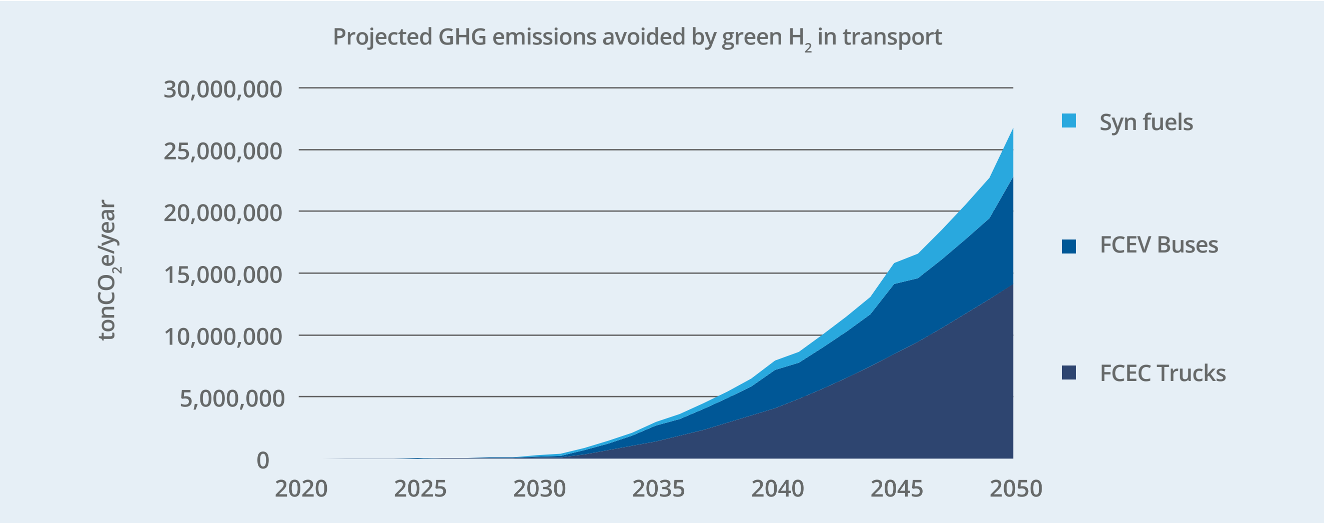
Replacing fossil fuels with green hydrogen for applications in power generation and industry has the potential of reducing up to 7.6 MtCO_2e/year in 2050, with around three-quarters of the reduction coming from the mining and metals industry, mostly from mining trucks and mineral reduction, and under one fifth to power generation in hydrogen turbines.

Figure 2-3. Projected GHG emissions avoided by the replacement of fossil fuels with green hydrogen in power generation and industry.



By 2050, substituting ICEVs with FCEVs and diesel with syn-fuels could reduce GHG emissions by up to 26.7 tonCO_2e/year, of which around half would come from FCEV trucks, one third from FCEV buses, and 15% from synthetic fuel use.

Figure 2-4. Projected GHG emissions avoided by green H_2 in road transport.



Water use and desalination: low impact on availability and cost

The process of splitting the water molecule into hydrogen and oxygen in an electrolyzer today requires approximately 16 liters of water per kilogram of green hydrogen and may reach 11 l/kgH_2 as efficiencies improve. In regions where the resource is scarce and sea water is available, such as the Baja California peninsula, water desalination will be required for hydrogen production.

From a case study of the second volume of this series on "Green Hydrogen integration into the grid" located in Baja California, a parametric value of 10,600 USD of investment in desalination plants of seawater per MW of electrolysis was obtained. This would imply an increase of less than 1% of the CAPEX per MW required for the electrolysis system alone, not including the additional investment in renewable energy and hydrogen transport and storage assets.

Social Impact: 90,000 jobs created in 2050

Over 90,000 people could be employed in the green hydrogen sector in Mexico in 2050. This is comparable to the 98,000 jobs in the renewable energy sector in Mexico in 2019 according to IRENA´s jobs database[2], and more than one-fifth of the people employed in the extractive industries in 2020 as reported by the National Employment Service[3].

The largest area of job creation is in the production of hydrogen itself and the required infrastructure, which is projected to employ nearly 1,600 people in 2030 and close to 58,600 workers in 2050.

The second largest area of employment would be in the hydrogen refueling infrastructure for vehicles, hiring over 360 people in 2030 and growing to 18,400 by 2050, of which around three quarters area indirect jobs.

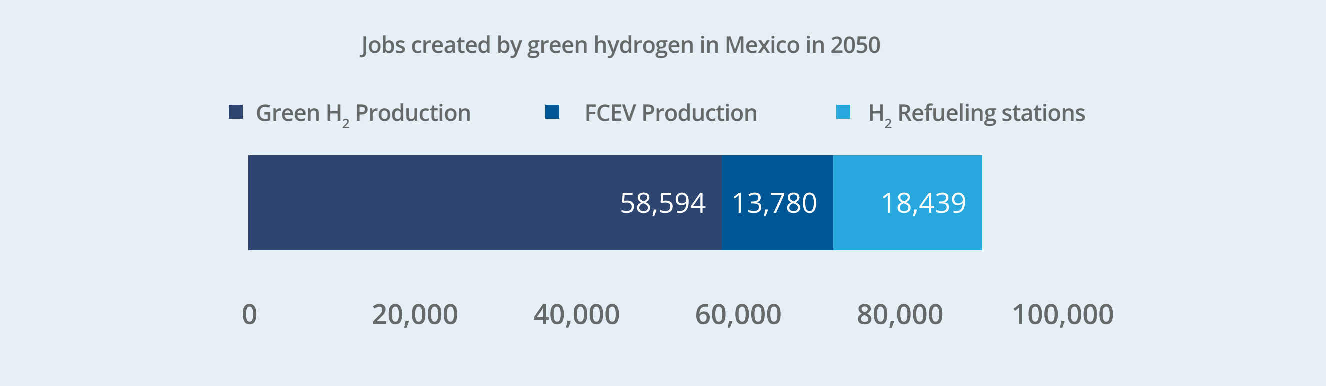
Table 2-1. Jobs created in green hydrogen infrastructure in Mexico.

Jobs created by green hydrogen in Mexico	Jobs in 2030	Jobs in 2050
Hydrogen Production	**1,596**	**58,594**
Construction and Installation	765	34,701
O&M	356	16,154
National Manufacture of Electrolyzers	475	7,739
FCEVs – Automotive Industry	**186**	**13,780**
Hydrogen Refueling Stations (HRS)	**363**	**18,439**
Direct Jobs HRS	90	4,580
Indirect Jobs HRS	273	13,859
Total Jobs created	**2,145**	**90,813**

2. IRENA, Renewable Energy and Jobs, 2020.
3. National Employment Service (SNE), Employment by economic sectors - Fourth quarter of 2020.

Third, the automotive industry would hire under 200 workers in 2030 but grow to employ nearly 13,800 workers by mid-century, of which around two-thirds would be directly employed in the manufacture of FCEVs.

Figure 2-5. Jobs created by green hydrogen in Mexico in 2050.

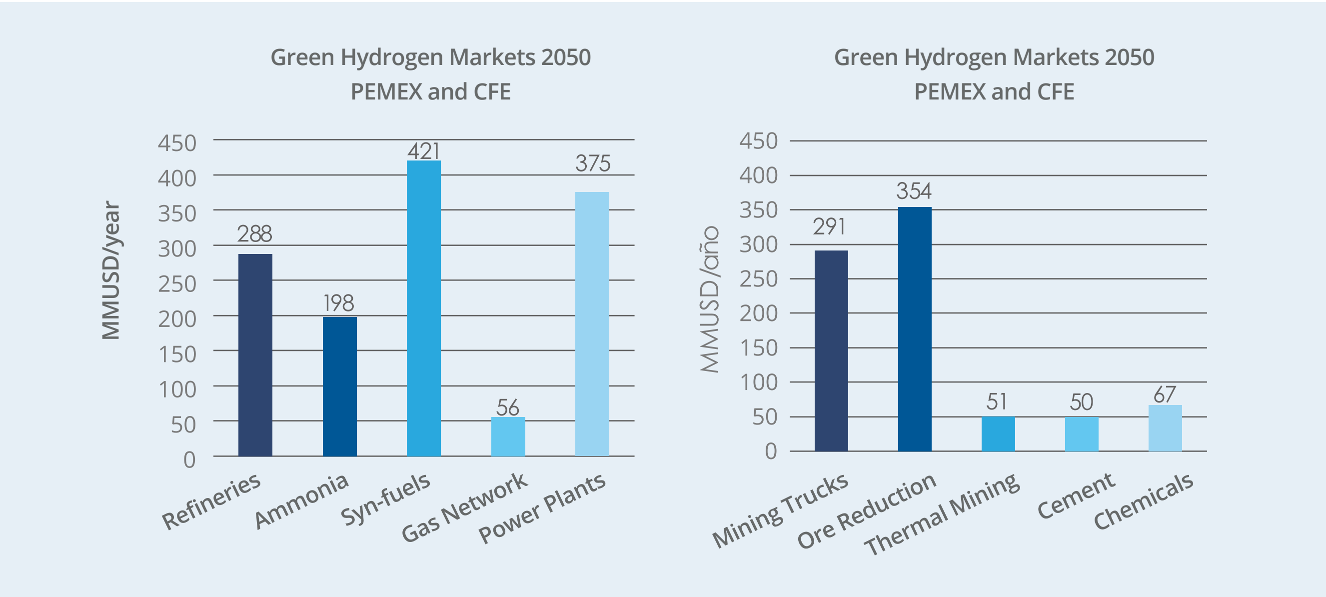


The creation of jobs associated with the development of the hydrogen sector in Mexico is revealed by an analysis done by Hinicio which gathers existing research from sources such as Navigant Consulting[4], Element Energy[5], and CE Delft[6] that estimates job creation with the deployment of hydrogen projects, yielding the full-time equivalent jobs created for each step of the hydrogen value chain by installed capacity or CAPEX investment.

Economic Impact: annual market of 5.7 billion USD created by 2050

The development of a green hydrogen sector in Mexico is projected to create new markets for different segments and applications, as well as the require investments, initially, for hydrogen production infrastructure. The yearly hydrogen market value and the CAPEX investments necessary to fulfill the hydrogen demand can be calculated using Hinicio models.

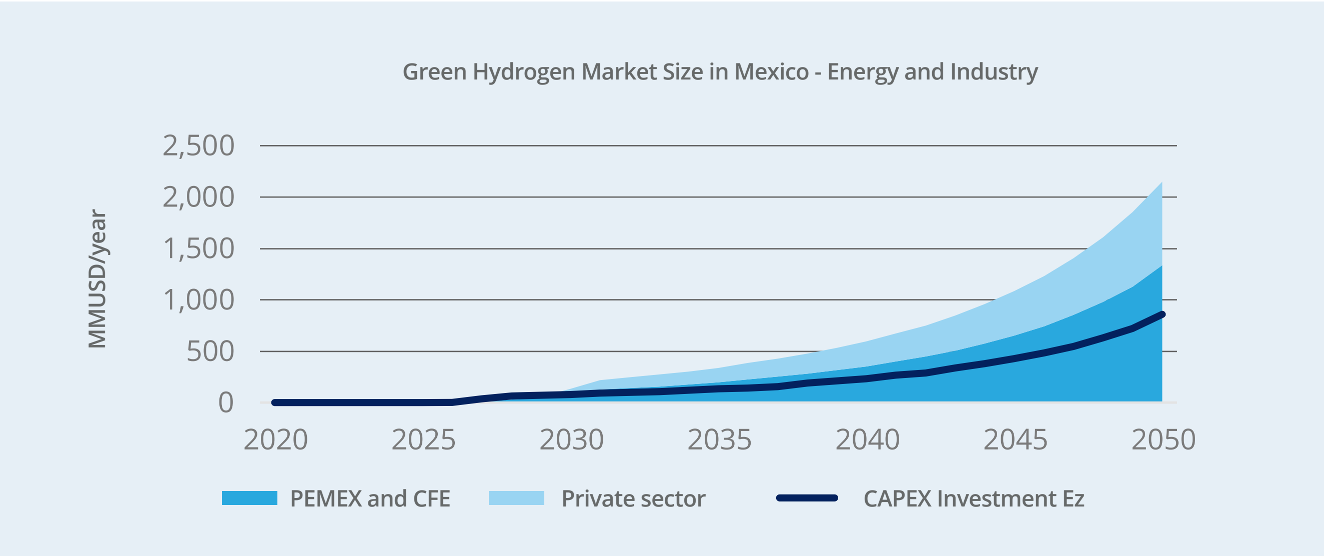
Figure 2-6. Green hydrogen market value by 2050 for segments mostly pertinent to PEMEX and CFE (left) and the private industry (right).



[4] Navigant, Gas for Climate – Job creation by scaling up renewable gas in Europe. 2019.
[5] Element Energy. Hy-Impact Series: Hydrogen for economic growth, 2019.
[6] CE Delft, Green hydrogen and employment, 2019.

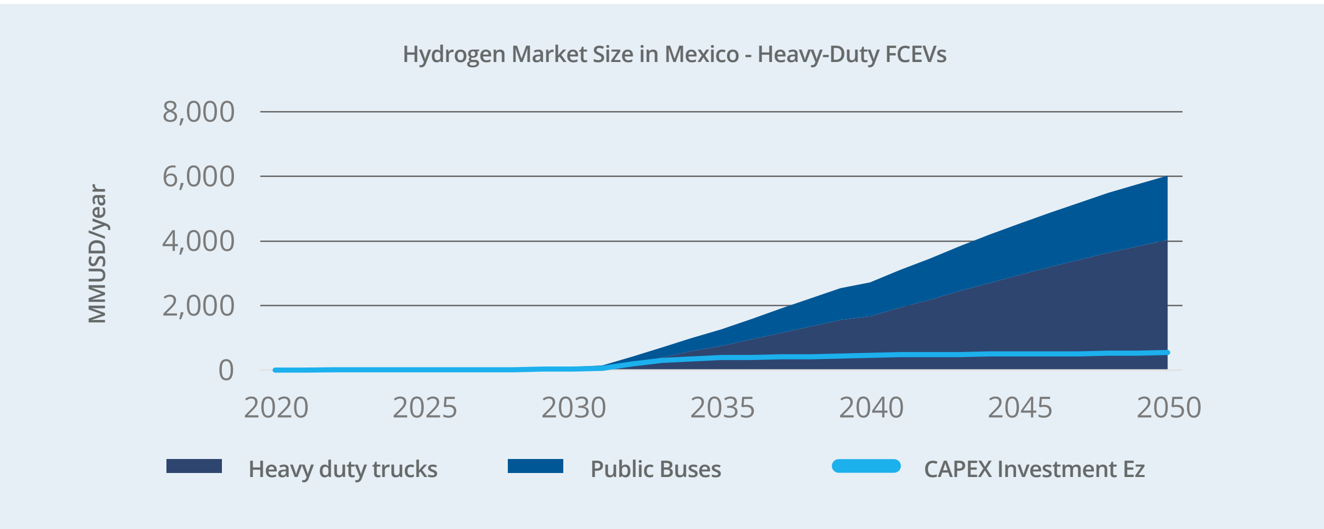
The joint expected impact for PEMEX and CFE is of roughly 100 million USD per year by 2030 and more than 1.3 billion USD yearly 2050 to supply their hydrogen demand. For PEMEX, the most notable impact is projected in the production of synthetic fuels, with a hydrogen market value of 420 MMUSD/year by 2050, followed by refineries with close to 290 MMUSD/year, and finally ammonia production with 200 MUSD/year. For CFE the largest economic impact is projected to be in the production of electricity in turbines powered by hydrogen and natural gas, with an H2 value of 375 MMUSD/year by 2050.

Figure 2-7. Hydrogen market size projections for energy and industrial uses[7].



The largest projected opportunities in hydrogen for the private industries are in FC CAEX and mineral ore reduction, which jointly account for nearly 80% of the economic impact valued at 800 MMUSD/year by 2050. Cumulative investments for supplying hydrogen to PEMEX and CFE are projected in close to 2.6 billion by mid-century, and in nearly 8.5 billion to supply the private industry.

Figure 2-8. Hydrogen market size projections for heavy-duty road transport.



[7] CAPEX Investment in electrolysis plants.

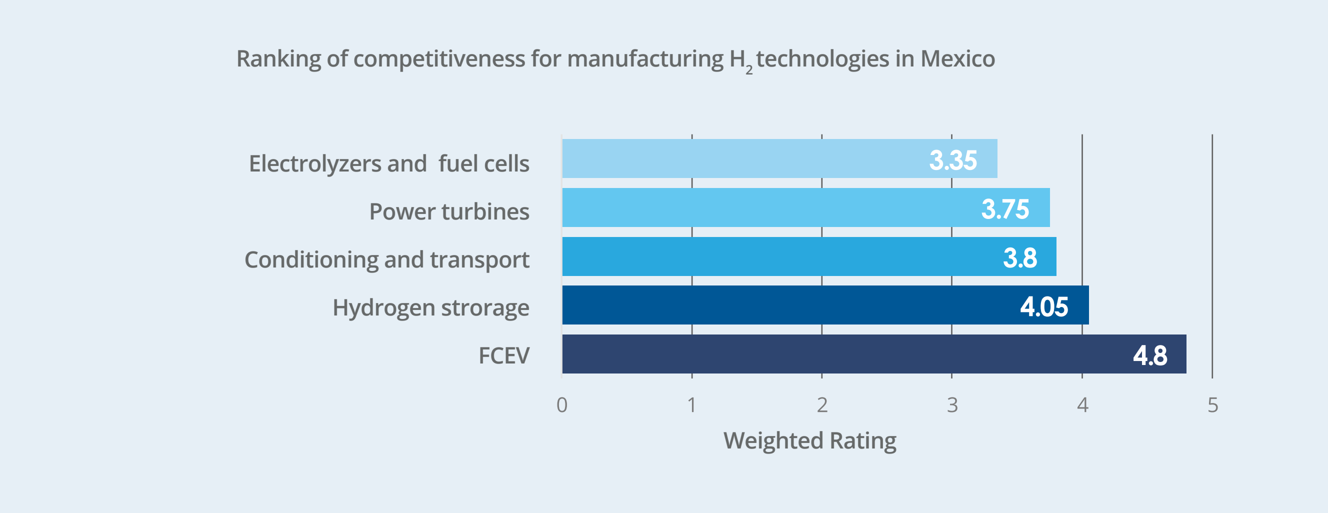
The heavy-duty road transport presents the largest economic opportunities for hydrogen in Mexico. Split into public transport buses and long-haul trucks, they represent a hydrogen demand that will accelerate quickly so that the hydrogen market for heavy duty transport is projected to reach 6 billion USD/year by 2050, split into 2 billion USD/year for public transport buses and 4 billion USD/year for freight trucks per year.

Cumulative investments of nearly 8.5 billion USD by 2050 are projected to supply the hydrogen demand for heavy-duty FCEVs in Mexico.

Manufacture of hydrogen technologies: high potential for the automotive industry

Established industries in Mexico such as metal-manufacturing, handling of industrial gases, aerospace, and automotive provide the basis for potential competitiveness the to manufacture hydrogen technologies in the country. They provide it with highly developed value chains, manufacture infrastructure, qualified talent and experience, and an overall high degree of adaptability to adopt new technologies and develop pioneering value chains and manufacturing ecosystems.

Figure 2-9. Ranking of the manufacture potential of hydrogen technologies in Mexico.



The analysis shows Mexico´s potential to be competitive in the manufacture of hydrogen power turbines as well as conditioning, transport, and storage equipment, which will require the development of dedicated talent and strengthening the manufacturing ecosystems for related technologies into a hydrogen component and equipment producing market.

The automotive industry could continue to thrive in the country, leveraging on a robust manufacturing ecosystem to adopt new hydrogen FCEV technologies. When also considering a strategic location in North America and access to both the Atlantic and Pacific oceans, Mexico displays the potential to position itself as a leading manufacturer of FCEVs worldwide.

3. Transport Sector: largest green hydrogen demand potential

Heavy-Duty Road Transport: half a million FCEVs on the roads by 2050

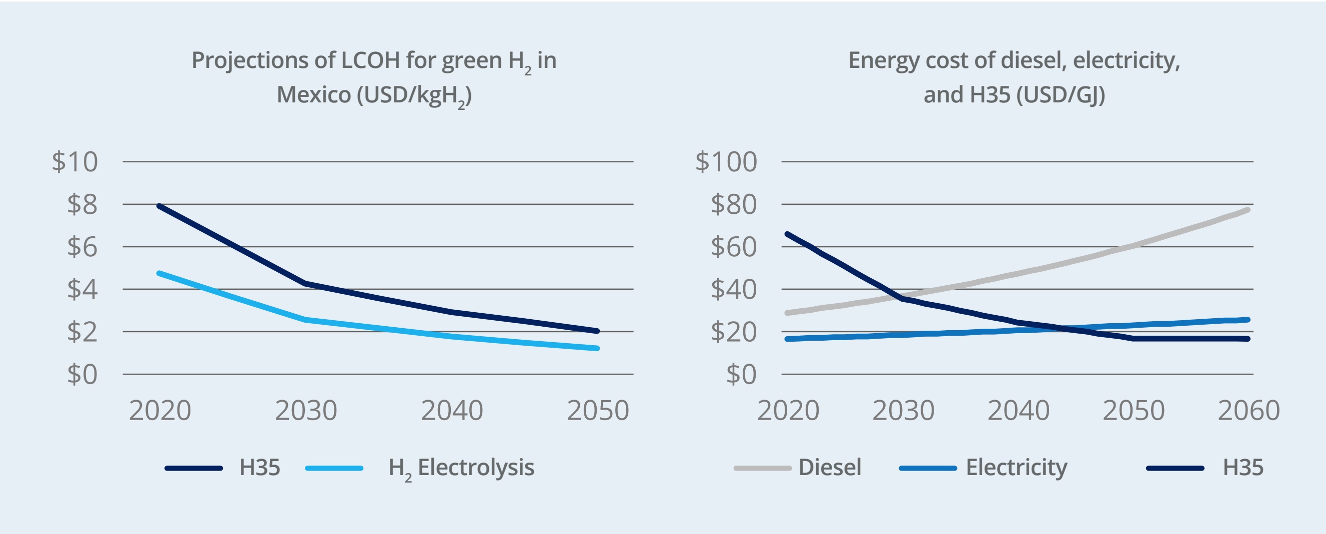
The segment which presents the largest business opportunities is road transport, among the first in which green hydrogen will reach cost competitiveness with public transport buses and freight trucks being cheaper than both conventional internal combustion engine vehicles (ICEVs) and battery electric vehicles (BEVs) on a total cost of ownership basis before 2030, which will boost early adoption. By 2050, up to 500,000 heavy-duty FCEVs could be on the roads servicing carbon-free public and freight transport in Mexico.

In Mexico, the transport sector is the largest GHG emitter, accounting for around one quarter of the national emissions. The electrification of the vehicle fleet is among the measures to comply with the reduction of 19% of the sector's emissions by 2030. Fuel cell and hydrogen heavy-duty trucks and buses could embody a highly promising zero-carbon alternative especially for the long-haul segment and in public transportation.

Fuel Cell Electric Vehicles (FCEV) store energy in the form of hydrogen as an energy carrier and use it to generate electricity in a fuel cell which in turn drives an electric powertrain to propel the vehicle. If fueled with green hydrogen, FCEVs provide a zero-emissions transport alternative.

FCEVs are positioning against batteries for electric mobility in the segments where long range and fast refueling is critical, such as buses and freight trucks. Fuel cell and hydrogen heavy-duty trucks and buses could embody a highly promising zero-carbon alternative especially for the long-haul segment and in public transportation.

Figure 3-1. Projected LCOH[8] for green hydrogen at the electrolyzer output and H35 (left), and cost of energy comparison from diesel, electricity and H35 (right).

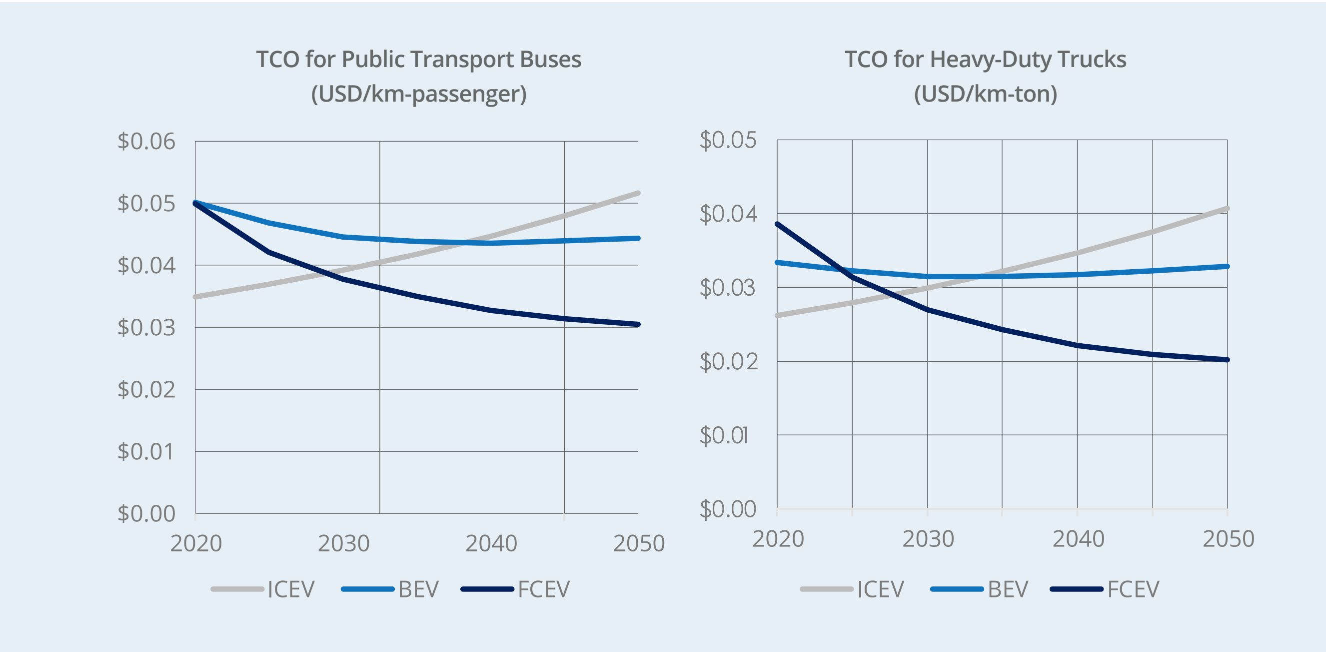


The hydrogen cost considered to power buses and trucks is of hydrogen compressed at 350 bar, or H35, which is its form of supply in HRS. Its cost increases by two-thirds relative to the cost of hydrogen produced at the electrolyzer output, attributed to its compression, transport, storage, and supply at the HRS.

[8] LCOH: Levelized Cost of Hydrogen

A Total Cost of Ownership (TCO) Analysis integrates all costs for the owner throughout the vehicle's lifetime and provides a basis to compare the cost of different vehicle technologies for a particular use. The analysis considers travel of 65,000 km/year for public transport buses and 160,000 km/year for heavy-duty freight trucks. TCOs for FCEVs will reach cost parity with BEVs and FCEVs before 2030 for both public and freight transport. The TCO breakdown shows that the highest cost for ICEVs both in 2030 and 2050 corresponds to energy (fuel), being considerably higher than for BEVs and FCEVs even before 2030. Acquisition costs remain the highest TCO components for both BEVs and FCEVs, with costs decreasing as technology upscales towards 2050.

Figure 3-2. TCO curves[9] for diesel, battery electric, and FCEV public transport buses (left), and heavy-duty freight trucks (right).



The joint projected hydrogen demand for public transport buses and trucks in Mexico is of 13 kilotons of H_2 per year in 2030, increasing at an exponential rate to around 550 kilotons of H_2 per year in 2040, and growing three-fold in the following decade to reach 1,780 kilotons of H_2 per year in 2050.

The projected electrolysis capacity will nearly reach 150 MW in 2030, grow over twenty times in the following decade to 6,200 MW in 2040, and reach nearly 19,500 MW by 2050.

The hydrogen market value of compressed hydrogen (H35) supplied at HRS is projected to be of over 50 million USD by 2030 and increase sharply to 1.6 billion USD in 2040 and 3.6 billion USD by 2050.

Table 3-1. Projected size of FCEV fleet for public transport buses and heavy-duty trucks.

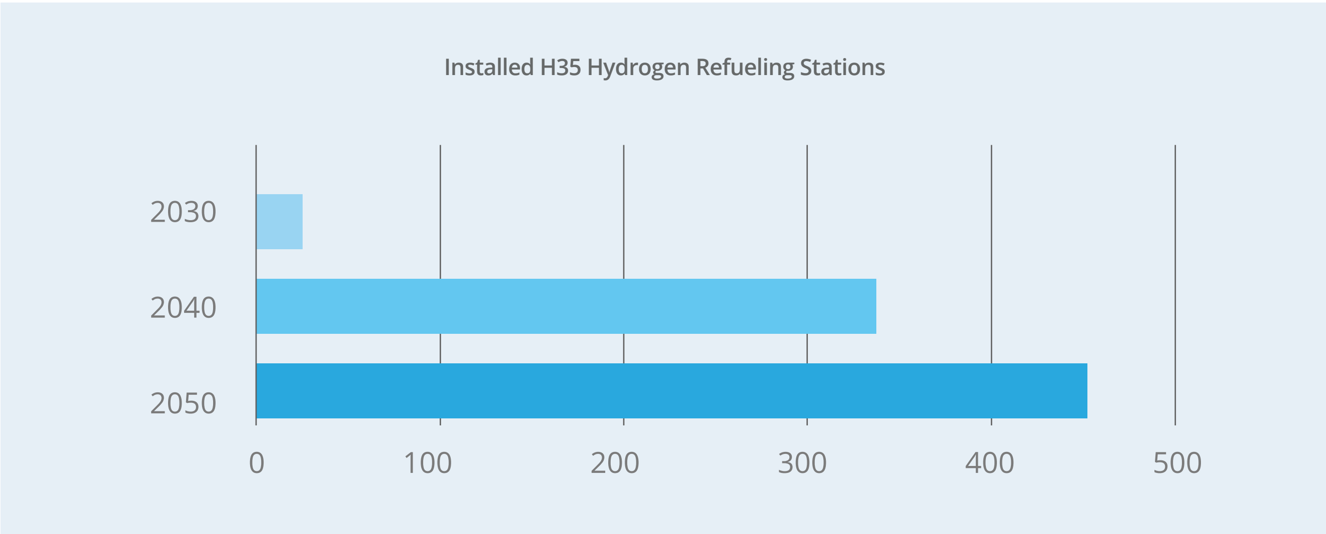
	FCEV Fleet		
Year	Buses	Trucks	Total
2030	1889	1,436	3,325
2040	93,055	69,633	162,689
2050	257,373	242,202	499,575

9. The TCO calculations consider travel of 65,000 km/year for public transport buses and 160,000 km/year for heavy-duty freight trucks for all technologies.

The share of hydrogen demand and the corresponding electrolysis capacity and market value fluctuates around 40% for public transport buses and 60% for heavy-duty trucks from 2030 to 2040 and transitions to around one third to public and two thirds to freight transport in 2050.

The projected H35 market values consider only its production and supply, while large complementary markets will also be created, for national production or import of FCEVs, components, dedicated maintenance service, hydrogen transport and refueling infrastructure, among other. The hydrogen refueling infrastructure is projected to grow as H_2 demand from FCEVs does, requiring an increasing number of HRS starting at 14 in 2030 and growing to 340 in 2040 and nearly 450 in 2050.

Figure 3-3. Projected number of H35 Hydrogen Refueling Stations for public transport and heavy- duty freight transport FCEVs in Mexico in 2030-2050.



Synthetic fuels could fuel the aviation industry in 2035

Synthetic fuels will be next in reaching cost parity in 2035 to power the aviation industry with carbon neutral fuel. These synthetic hydrocarbons produced by combining green H_2 with captured CO_2 could substitute roughly 9,200 barrels of oil equivalent per year by 2050, supplying 12% of aviation's fuel demand, and contributing to one third of the transport sector's emissions reduction targets as set in Mexico's NDC. For this application alone, 3,500 MW of electrolysis capacity would be required by mid-century. Further context and analysis on synthetic fuels can be found in Volume 5. Green Hydrogen in State-Owned Companies.

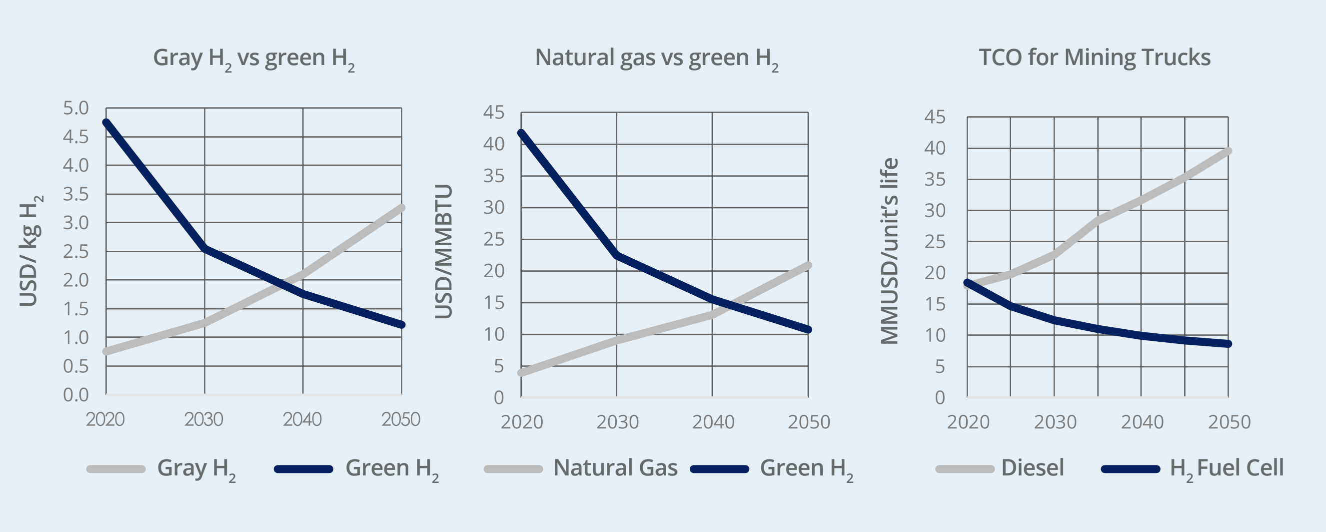
4. Green Hydrogen in Industry: 80% of demand in the mining sector

Companies worldwide see green hydrogen as a key vector for the decarbonization to comply with climate goals and the advent of the hydrogen economy is expected to set the ground for new business opportunities and value creation.

The mining sector: mining trucks and mineral reduction will boost green H_2 demand

The largest area of opportunity for green hydrogen in industry is in the mining sector, with a demand that could reach half a million tons per year by 2050. 50% of this demand would power 1,500 fuel cell mining trucks, 42% would be used to reduce one quarter of the country's iron ore for steel making, and 8% to supply 4.3 PJ of energy for the industry's thermal applications. Together they would account for over 80% of the non-transport private sector demand by 2050.

Figure 4-1. Cost curves of gray hydrogen vs green hydrogen (left), natural gas vs green hydrogen (center), and TCO of diesel and H_2 FCEV mining trucks (right).



Thermal applications in the chemical industry and cement manufacture: moderate green H_2 demand

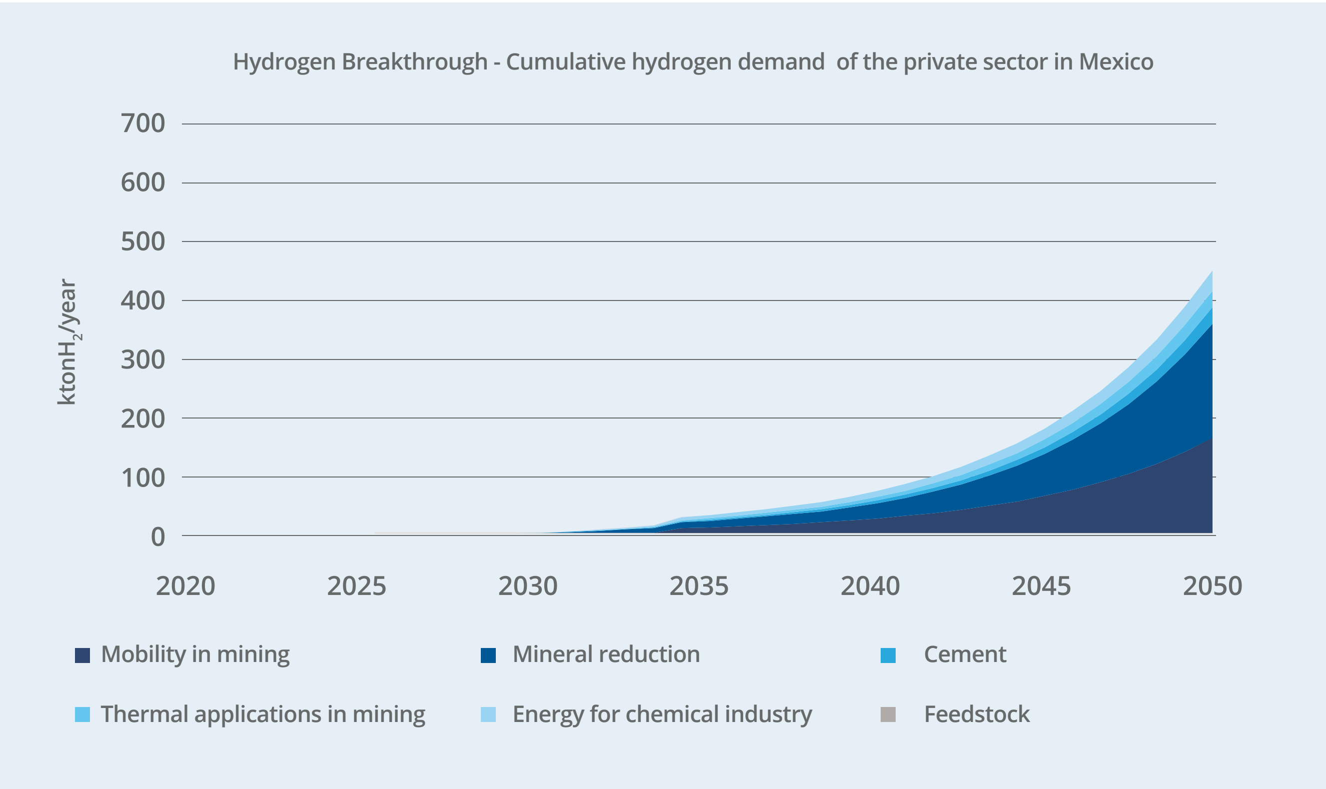
Thermal applications in the chemical industry and cement manufacture will present a moderate green H_2 demand, requiring 520 MW and 400 MW of electrolysis, respectively, and jointly replacing up to 350 billion cubic feet of natural gas per year by 2050. Opportunities as a chemical feedstock for flat glass, synthetic resins, and margarines will be negligible in comparison to the total national green hydrogen market, where even a full 100% green H_2 supply would demand barely 3,500 ton/year by 2050.

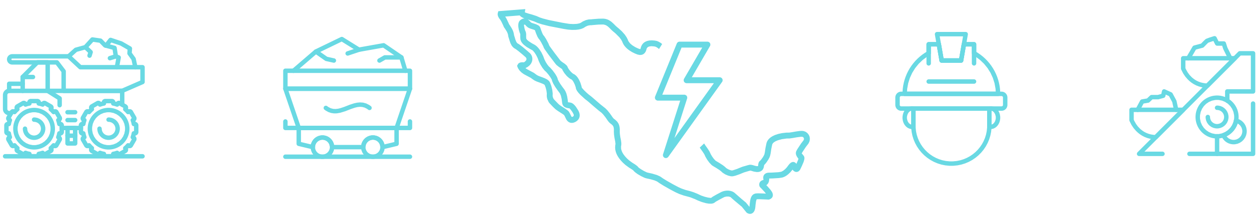
Prevalence remains for mobility applications in mining and mineral reduction, which together account for nearly 80% of the projected demand by 2050. A more favorable environment allows for 200 MW of electrolysis capacity to be in place by 2030, from early deployments across all segments except for industry feedstock and a yearly production of green hydrogen of 17,000 tons. An accelerated deployment will be seen in the following decade as most applications achieve cost parity or become closer to it, with demand growing more than seven times in that period to reach 120,000 tons per year and more than 1,400 MW of electrolysis capacity in 2040.

By mid-century green hydrogen demand growths further to reach a staggering 250 thousand tons per year for mineral reduction, 210 thousand for mobility in mining, and still considerable but more moderate demands for thermal applications in the chemical and mining industries and use in cement, all three in the range between 35 and 45 thousand tons per year. For use as industry feedstock the hydrogen demand remains minor and even assuming a full substitution from gray to green hydrogen for flat glass, synthetic resins, and margarine, their combined demand would not reach 4 thousand tons per year.

In 2050 the cumulative demand of green hydrogen for all the industries studied will reach 580,000 tons per year, requiring 6,750 MW of electrolysis capacity, and have a value of over 700 million dollars.

Figure 4-2.Projected hydrogen demand for all end uses for the private sector in Mexico.





5. Green Hydrogen for PEMEX and CFE: 11 GW of electrolysis by 2050

State-owned PEMEX and CFE could become major players in the green hydrogen sector in Mexico to decarbonize their operations with supply independent from hydrocarbons, with over 11GW of potential electrolysis demand by 2050.

PEMEX: Sizeable opportunities in refineries, ammonia, and synthetic fuels

By 2050, nearly 1,350 kilotons of green ammonia would be produced yearly to fabricate fertilizers, over 750 thousand barrels of oil would be refined using green hydrogen every day, and the Mexican demand for synthetic fuels will have surpassed 1.4 million liters every year. This would drive PEMEX's green hydrogen demand to over 650 kilotons per year, requiring more than 7.5 GW of electrolysis capacity, and would result in a green hydrogen supply worth 800 million USD per year in 2050.

CFE: Largest potential in hydrogen-powered turbines

For CFE, a relatively small demand is expected for injection in the gas network due to a low economic competitiveness. The largest opportunities are projected in hydrogen thermal power plants to power the equivalent of nearly 670 MW of CCGTs with green hydrogen in 2050, accounting for more than 87% of its hydrogen demand of 310 kilotons per year. Supplying CFE's green hydrogen needs would require an installed capacity of electrolysis of around 3.5 GW and have a cost of 380 million USD every year by mid-century.

PEMEX and CFE could lay the foundations for the development of a large-scale green hydrogen economy in Mexico

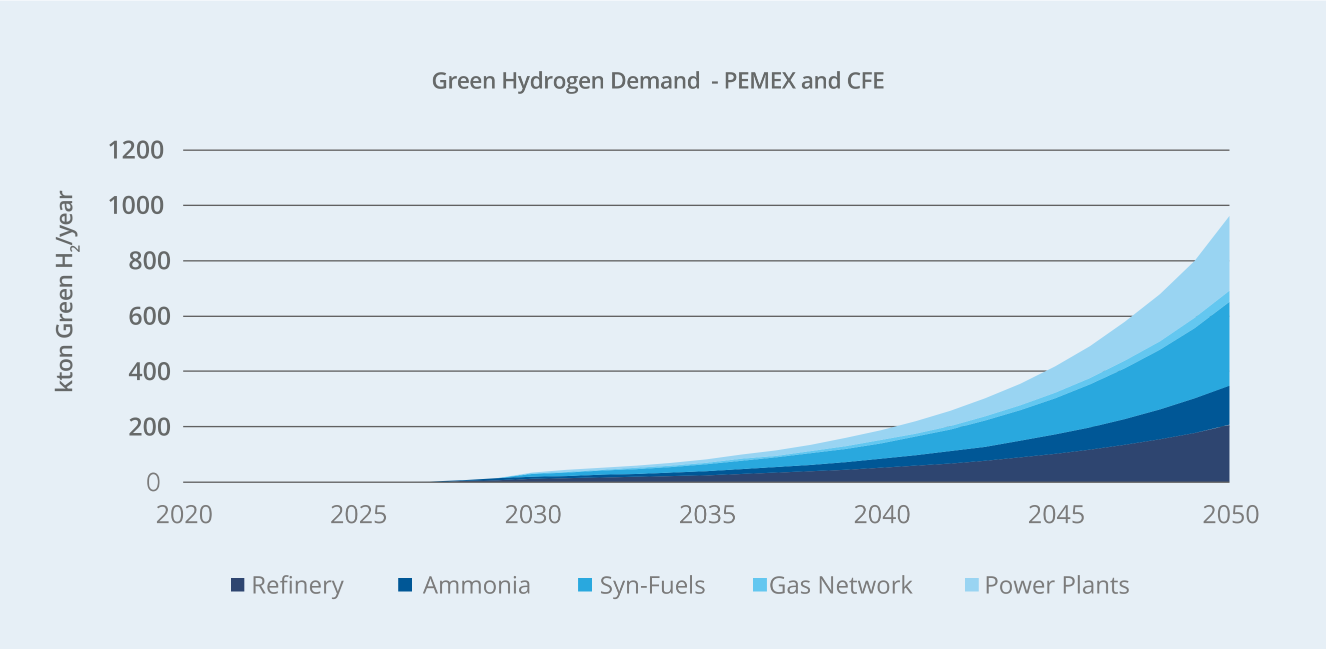
Once being cost-competitive, fossil-free and locally produced green hydrogen could provide a lower cost and low carbon alternative independent of foreign supply of hydrocarbons and the cost fluctuations of international oil markets that could provide benefits to both companies and Mexico's energy sovereignty, allowing for larger portions of each end-product's[10] value chain to remain in the country along with the associated investments, jobs, and infrastructure. Hydrogen adoption is projected to boom in the 2040s, but could be accelerated drastically by adopting goals oriented with the sovereign energy transition and measures to comply climate commitments, such as setting a price on CO_2.

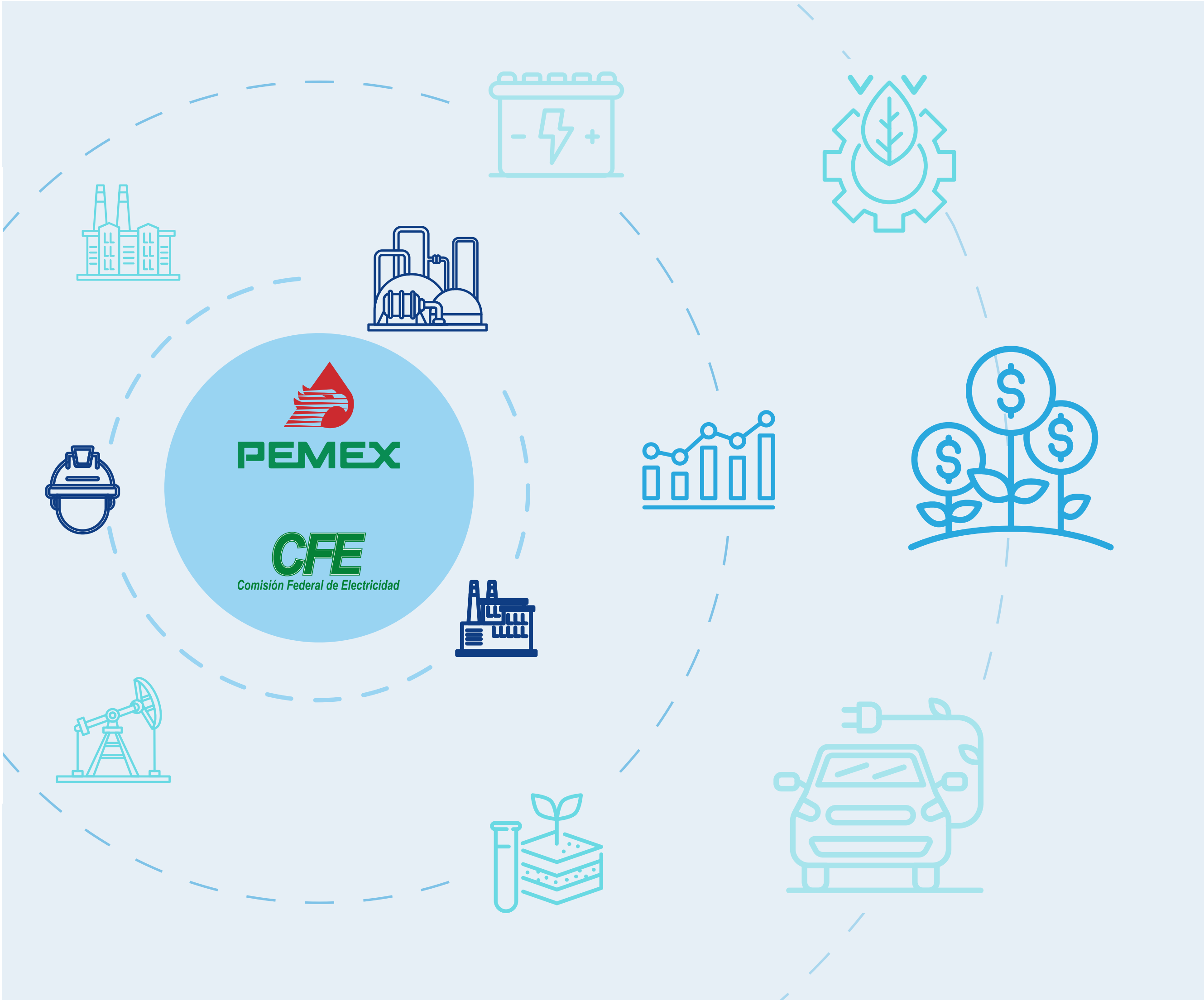
This would allow for hydrogen to become cost-competitive earlier in time and enable an advanced deployment of hydrogen technologies in Mexico.

Even if no climate or hydrogen specific incentives are in place, Mexico's state-owned companies have the potential to drive the creation of an extensive green hydrogen market in country under the aggressive but realistic assumptions of the Hydrogen Breakthrough scenario. Following these assumptions, PEMEX and CFE could jointly enable the deployment of 11 GW of electrolysis in Mexico, reaching nearly one million tons of hydrogen demand worth close to 1.2 billion USD per year by 2050.

[10] End-products for the applications addressed in this report include petrochemicals, fertilizers, liquid fuels for air and maritime transport, thermal energy, and electricity.

Figure 5-1. Projected hydrogen demand for all end uses for state-owned companies.





6. Integration of Green Hydrogen in the Grid: Low impact

Green hydrogen energy storage could increase 2% of renewable generation in 2050.

Hydrogen energy storage is far from being the most competitive storage alternative, ranking in 7th out of 11 evaluated technologies. For 2030 the re-electrification of hydrogen will be almost nonexistent in the scope of the 100GW+ national power system, with 1 GW of electrolysis capacity needed to produce hydrogen for a 300 MW hydrogen open cycle gas turbine for re-electrification.

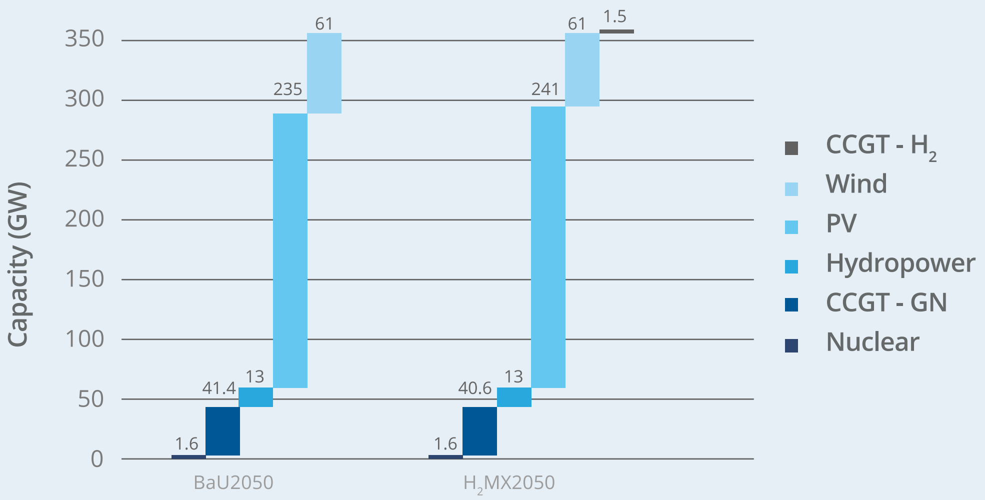
It is only in 2050 that hydrogen could become more relevant in the national power system, driven mainly by the improvement in costs and performance seen in current trends. In 2050, about 5.5 TWh/year will be produced from hydrogen re-electrification, that is about half of the current nuclear power generation. For this, around 1.5 GW of hydrogen-powered combined-cycle gas turbines (CCGT-H_2) will be needed, which is large for the development of green hydrogen projects for its supply but small when compared to the more than 300 GW of installed capacity in the national power system.

Hydrogen integration will allow to increase renewable generation in the national electric system. The results show that with the hydrogen re-electrification there are additional 15 TWh/year generated from renewable sources in 2050, nearly a 2% increase relative to a scenario without hydrogen, as shown in Figure 6-1. The water consumption analysis reveals that the water required to produce the hydrogen needed to supply the CCGT-H_2 accounts for less than the 0.1% of the current consumption in each region of production.

Mulegé, B.C.: green H_2 favors the deployment of low-cost PV generation

An analysis focused on for the power system of Mulegé, Baja California reveals that hydrogen integration enables a competitive storage solution for the cheap solar energy of this region, seeing a local reduction of wind capacity from 108 MW to 30 MW and an increase in PV capacity from 302 MW to 407 MW when introducing hydrogen energy storage in 2050. Overall energy storage capacity also increases from 0.9 GWh to 2.4 GWh, of which 1.7 GWh are in the form of hydrogen energy storage with around 50 ton.

Figure 6-1. Installed capacity for Mexican power system by 2050 for the two evaluated scenarios.



7. Hydrogen Exports

Mexico: a competitive hydrogen exporter to Europe and Asia

Mexico has the potential to become a strong exporter of green hydrogen. As early as 2030 more than 300 million USD of green H_2 could be exported overseas. When compared to potential large exporters of green hydrogen, Mexico is placed as a competitive long-distance exporter to Europe and Asian markets, given a low hydrogen production cost its privileged geographic position with access to both the Atlantic and the Pacific Oceans and its northern latitude and competing with Chile and Australia.

A comparative analysis is performed to assess the cost competitiveness of hydrogen import-export shipping routes. A shipping distance matrix was built with the distances in nautical miles between all possible combinations. Also inputting the production cost at exporting countries, a final LCOH delivered at the import destination was calculated[11] for each producing and consuming country combination assuming overseas transport as liquid hydrogen, as shown in Table 7-1.

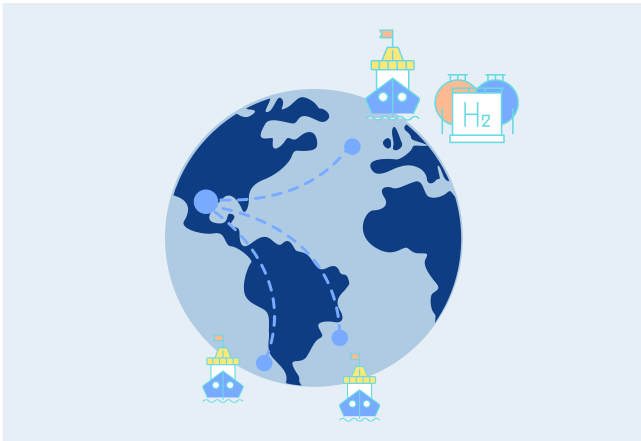


Table 7-1.Projected LCOH at the port of destination for each hydrogen trade route, with Mexico's ranking withing the studied exporters for each destination.

LCOH at Destination (USD/kgH_2)	Origin				Mexico's Ranking
Destination	**Australia**	**Chile**	**Mexico**	**Morocco**	
European Union	6.15	5.32	5.52	4.78	3
Japan	5.38	5.65	5.60	5.78	2
South Korea	5.29	5.65	5.53	5.67	2
United Kingdom	6.25	5.41	5.60	4.87	3

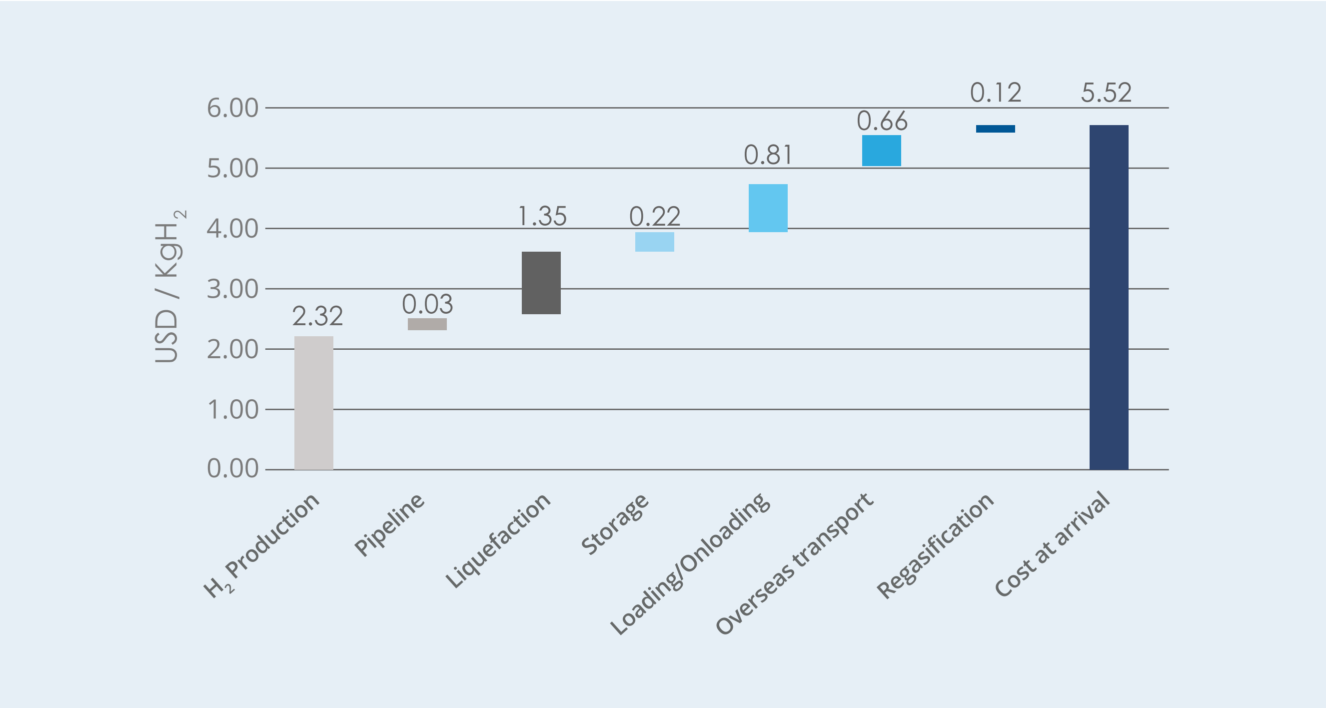
A breakdown of the costs of the hydrogen delivered at port shows that around half of the costs are fixed and half vary with local production of hydrogen and shipping distance, which accounts for the differences in cost depending on the country of origin and destination.

Mexico would the second or third most competitive exporter to all destination markets in the study, given a low hydrogen production cost its privileged geographic position with access to both the Atlantic and the Pacific Oceans and its northern latitude, shortening shipping distance to the main importers.

Further analysis was made in this study to estimate the share of the hydrogen demand that Mexico could supply to the target overseas markets, resulting into hydrogen exports by 2030 of 60 thousand ton with a yearly market value of 330 million USD and requiring nearly 700 MW of electrolysis to produce.

[11] The LCOH of the hydrogen delivered is calculated using an Hinicio model and includes the costs of production, conversion to liquid, shipping, terminals, reconversion, and distribution by pipeline.

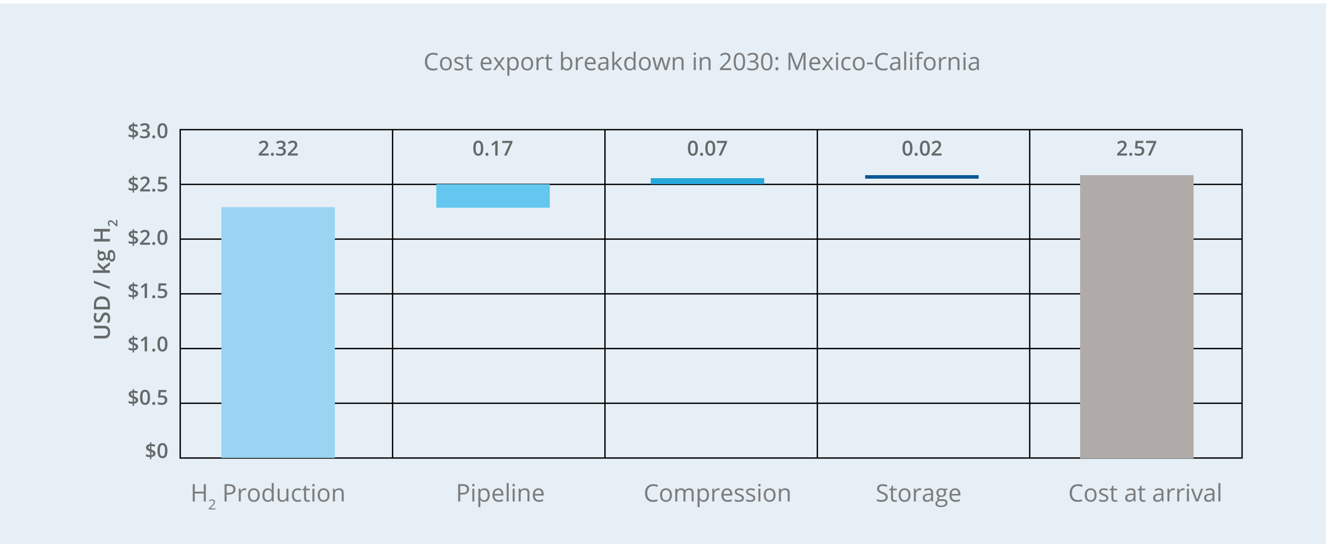
Figure 7-1.Hydrogen export breakdown by cost components from Mexico to the EU in 2030.



California: Low-cost hydrogen could be delivered by pipeline

An additional analysis was made to assess the export of green hydrogen from Mexico to California by land through pipelines, assuming a short distance travelled by pipeline of under 200 km. Mexico could deliver green H_2 by pipeline to California as cheap as 2.57 USD/kg in 2030, of which 90% are production costs and 10% are associated to its transport, compression, and storage.

Figure 7-2. Hydrogen export breakdown in 2030 by cost components from Mexico to the California.



Mexico's abundant renewable energy resources and privileged position provide it with a great potential to export hydrogen to international markets, further creating business opportunities and contributing to international hydrogen and energy transition needs.

8. Barriers and Recommendations

To reach its green hydrogen potential, Mexico has already developed many intellectual, financial, and legal capabilities. However, the country´s climate policy should be reconsidered, promoting renewable energies from political and regulatory standpoints, guaranteeing the protection of investments, developing a National Hydrogen Roadmap with defined targets and actions, and allocating funding and incentives for the development and adoption of green hydrogen infrastructure and technologies.

These measures could allow green H_2 to become cost-competitive up to a decade before than a Business-as-Usual scenario and enable an accelerated deployment as early as the 2030's. In a less favorable BaU scenario without strong public support to green hydrogen, renewable energy, and climate measures, the projected green hydrogen opportunities could be cut by half for the private sector and reduced up to seven times for PEMEX and CFE with significant expected decrease in road transport and hydrogen export opportunities as well.

A collection of barriers for green hydrogen in Mexico were identified throughout the analyses in this series of reports, and additional barriers and inputs for recommendations were gathered from interviews with relevant actors in Mexico. They are presented below under four categories.

Policy and Regulation: Green hydrogen strategies and regulatory certainty are needed

Barriers:

Mexico's regulatory and policy framework will be insufficient to comply with its international climate commitments; there are no national or state policies or roadmaps for the development of hydrogen in Mexico; and the regulation for the use of hydrogen in Mexico is unspecific for mostly all its possible applications. Furthermore, Mexico is perceived by the private sector to have an ecosystem unsuitable for investment in innovation.

Recommendations:

Rethink and update Mexico´s climate change policy, recognize hydrogen's potential benefits and develop state and national policies to support its deployment, and create a National Hydrogen Roadmap with defined targets and actions to achieve them along with hydrogen-specific regulations for its different applications.

Economic and Political Context: Promotion of renewables will boost green H_2 adoption

Barriers:

In Mexico access to energy infrastructure is highly concentrated and presents significant entry barriers, moreover, the availability of renewable power generation plants in Mexico is not favorable for the deployment of large-scale hydrogen projects. Additionally, Mexico's access to low-cost natural gas from the U.S. poses challenges in green hydrogen's competitiveness.

Recommendations:

Promote renewable energies from a political and regulatory standpoint, put in place measures that facilitate access to energy infrastructure for the development of hydrogen projects, and foster collaboration between specialized hydrogen companies and PEMEX and CFE. Establish Guarantees of Origin systems for green hydrogen and incentivize its adoption recognizing its environmental benefits.

[12] BaU: Business-as-Usual, escenario bajo el cual México cumple con sus NDCs pero no se toman medidas adicionales para impulsar al hidrógeno verde o en acción climática

Technology and Human Capital: Hydrogen funding, talent, and outreach are required

Barriers:

There is a high cost-competitiveness gap of green hydrogen production and consumption technologies, a lack of awareness of the uses of hydrogen and its potential impacts and limited or unlinked human resources from trained in green hydrogen to abate these challenges.

Recommendations:

Provide funding and financial assistance to hydrogen technology development, scale-up, and implementation, which could come from public, private, multilateral banking sources or a combination of them. Actively communicate the workings and benefits of green hydrogen to all stakeholders, create learning missions, and international partnerships that include knowledge transfer programs. Finally, set up a strategy to develop qualified talent in green hydrogen by fostering dedicated training, academic-industry partnerships, and international cooperation in higher education, research, development, and innovation.

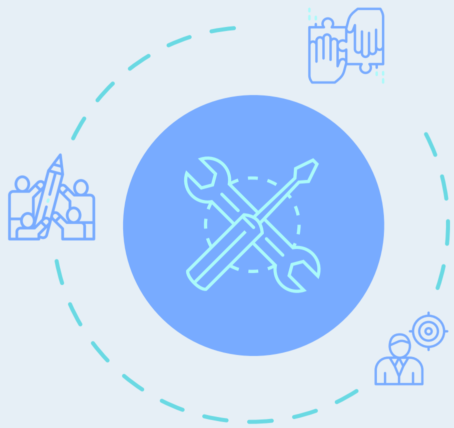
Capacity development: Mexico should leverage on and develop existing competences.

Mexico has many intellectual, financial, and legal capacities already developed. However, the adoption of the green hydrogen economy will demand the country to expand and develop new capabilities. The training of qualified human resources is required including public policy specialists for green hydrogen, technologists at different points in the hydrogen value chain, Health, Safety & Environment (HSE) specialists, hydrogen market researchers and data analysts, and hydrogen communication experts.

In financial capacities, Mexico should create or adapt financing mechanisms to foster the development of green hydrogen projects, quantifying the externalities and/or co-benefits, and facilitate the access to international funds for hydrogen development in Mexico.

Regarding legal capabilities, energy, environment, and industry law experts are required, along with the strengthening of autonomous regulatory bodies that provide investment certainty and promote competitiveness, and mechanisms to promote legal best practices and the inclusion of inputs from all relevant stakeholders.

As for commercial capabilities, internally, the ability to create differentiated markets between regular and low carbon products; and externally, to develop green hydrogen export capabilities, understanding the export value chain, target markets, and Mexico's competitive potential.



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