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Green Hydrogen in Mexico: towards a decarbonization of the economy

Volume III: Opportunities for the State Productive Enterprises PEMEX and CFE

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Abbreviations

ANIQ	National Chemical Association, Mexico
BOE	Barrels of Oil Equivalent
CAPEX	Capital Expenditures
CCGT	Combined Cycle Gas Turbine
CCUS	Carbon Capture, Use, and Storage
CFE	Comisión Federal de Electricidad
EJ	Exajoule
GHG	Greenhouse Gas Emissions
ICE	Internal Combustion Engine
IFA	International Fertilizer Association
KTPA	Kilotons Per Annum
LCOH	Levelized Cost of Hydrogen
LULUCF	Land Use, Land-Use Change, and Forestry
MMSCFD	Million Standard Cubic Feet per Day
MW	Megawatt
NDC	Nationally Determined Contributions
OPEX	Operational Expenditures
PEMEX	Petróleos Mexicanos
PRODESEN	National Electric System Development Program
SEMARNAT	Secretaría del Medio Ambiente y Recursos Naturales, Ministry of the Environment and Natural Resources
SENER	Secretaría de Energía, Ministry of Energy
SMR	Steam Methane Reforming (H_2 production)
SNR	National Refining System

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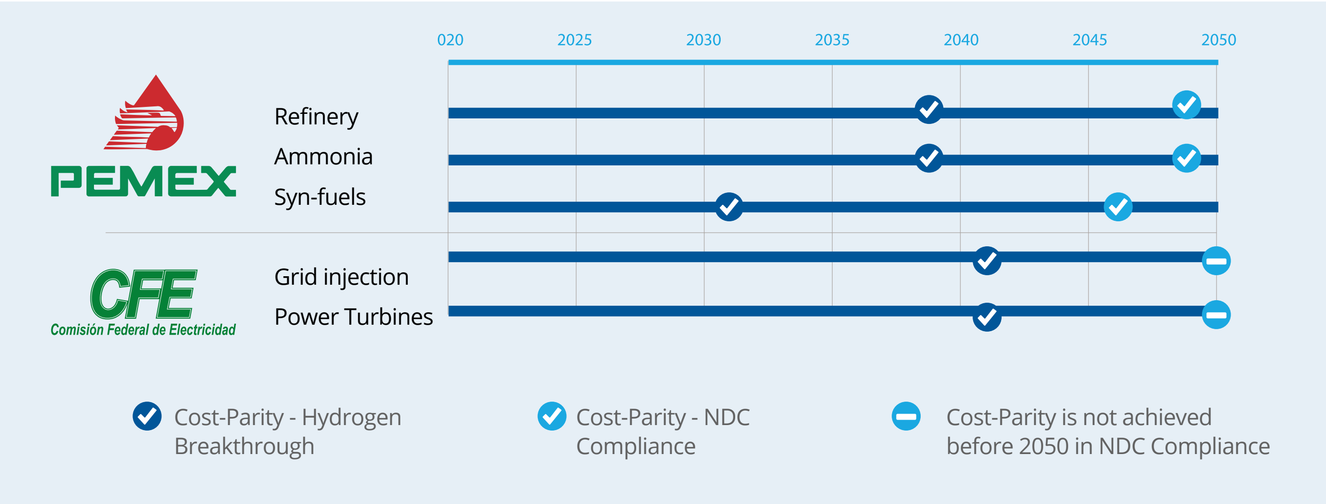
Executive Summary

PEMEX and CFE could become major players in the green hydrogen economy in Mexico to decarbonize their operations with supply independent from hydrocarbons.

Two realistic scenarios are presented: ‘NDC Compliance’(NDC), which lays out a base scenario that assumes Mexico will fulfill its climate commitments to comply with the Paris Agreement; and ‘Hydrogen Breakthrough’ (H_2B), which makes more optimistic assumptions following the projections of the Hydrogen Council. Cost projections for green hydrogen were made for both scenarios. The widest projected LCOH gap is in 2030 with 3.25 USD/kg in NDC and 2.55 in H_2B, following a sharp decline in hydrogen technology costs in the preceding decade. LCOH in 2050 for NDC Compliance is still over 20% higher than Hydrogen Breakthrough with 1.50 and 1.22 USD/kg, respectively.

Economic competitiveness of green hydrogen remains a challenge in both scenarios, with mild adoption for NDC projections even by mid-century. However, the H_2B scenario reveals opportunities for both PEMEX and CFE across applications to spearhead the Mexican green hydrogen economy, with over 11GW of potential electrolysis demand by 2050. The more favorable technology, policy, and business environment of this scenario projects a total hydrogen demand seven times larger than under NDC Compliance scenario by 2050.

Figure 1. Projected times of cost-parity of green hydrogen for all end uses.



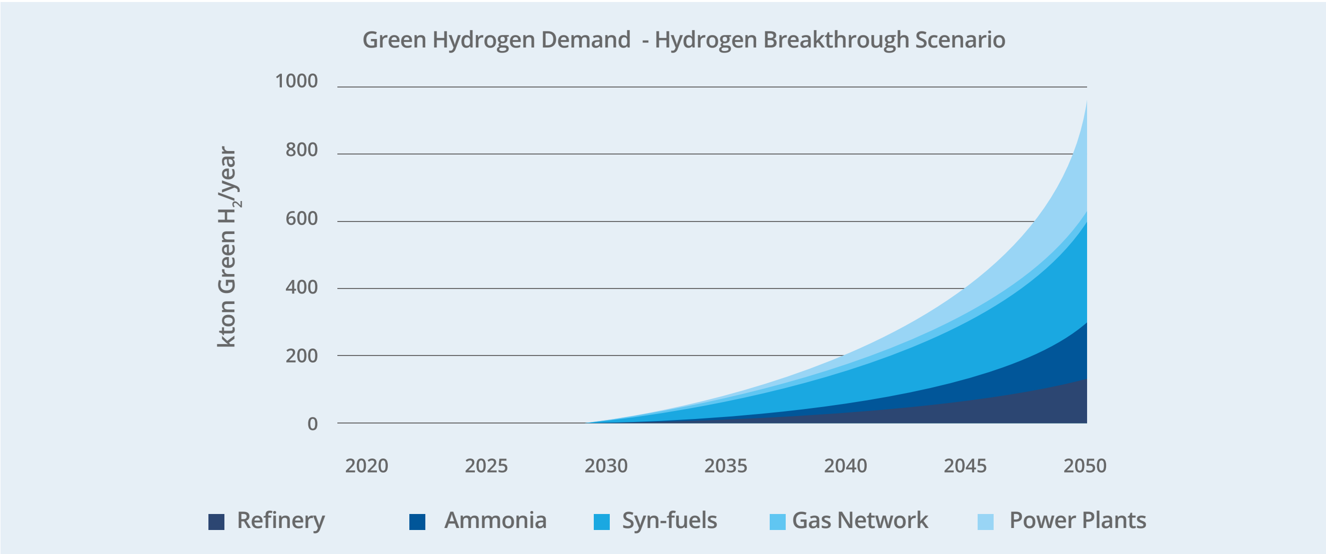
In the NDC Compliance scenario green hydrogen is expected to struggle to reach economic competitiveness in Mexico for most applications, with minor adoption for all end uses usually driven by climate mandates, and just starting to rise in the last years before 2050, when it is expected to reach cost parity and allowing for only localized opportunities for both PEMEX and CFE before 2050.

In the Hydrogen Breakthrough scenario, a more uniform deployment across all segments is projected, with higher rates of growth in the decade of 2040 and reaching a demand of nearly one thousand kilotons of green hydrogen per year by 2050.

Sizeable opportunities could be expected for PEMEX 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.

For CFE a relatively small demand is expected for injection in the gas network due to a low economic competitiveness even in this scenario and the largest opportunities are projected in hydrogen-powered 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 cost have a cost of 380 million USD every year by mid-century.

Figure 2. Projected hydrogen demand for all end uses in Hydrogen Breakthrough scenario.



State-owned 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[1] 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.

Table 1. Projected electrolysis deployment and yearly hydrogen markets in 2050 for PEMEX (refineries, ammonia, syn-fuels) and CFE (gas network, power plants).

2050	PEMEX		CFE	
	Electrolysis	H_2 Market	Electrolysis	H_2 Market
NDC Compliance	770 MW	97 MMUSD/year	720 MW	90 MMUSD/year
Hydrogen Breakthrough	7.5 GW	800 MMUSD/year	3.5 GW	380 MMUSD/year

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

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.

Table 2. Hydrogen demand and electrolyser capacity for all end uses in 2030 and 2050 (ktpa: Kiloton per annum).

All end uses for PEMEX and CFE	Hydrogen Demand (ktpa)		Electrolysis Capacity (MW)	
	2030	2050	2030	2050
NDC Compliance	5 ktpa	130 ktpa	60 MW	1,500 MW
Hydrogen Breakthrough	30 ktpa	960 ktpa	400 MW	11,200 MW

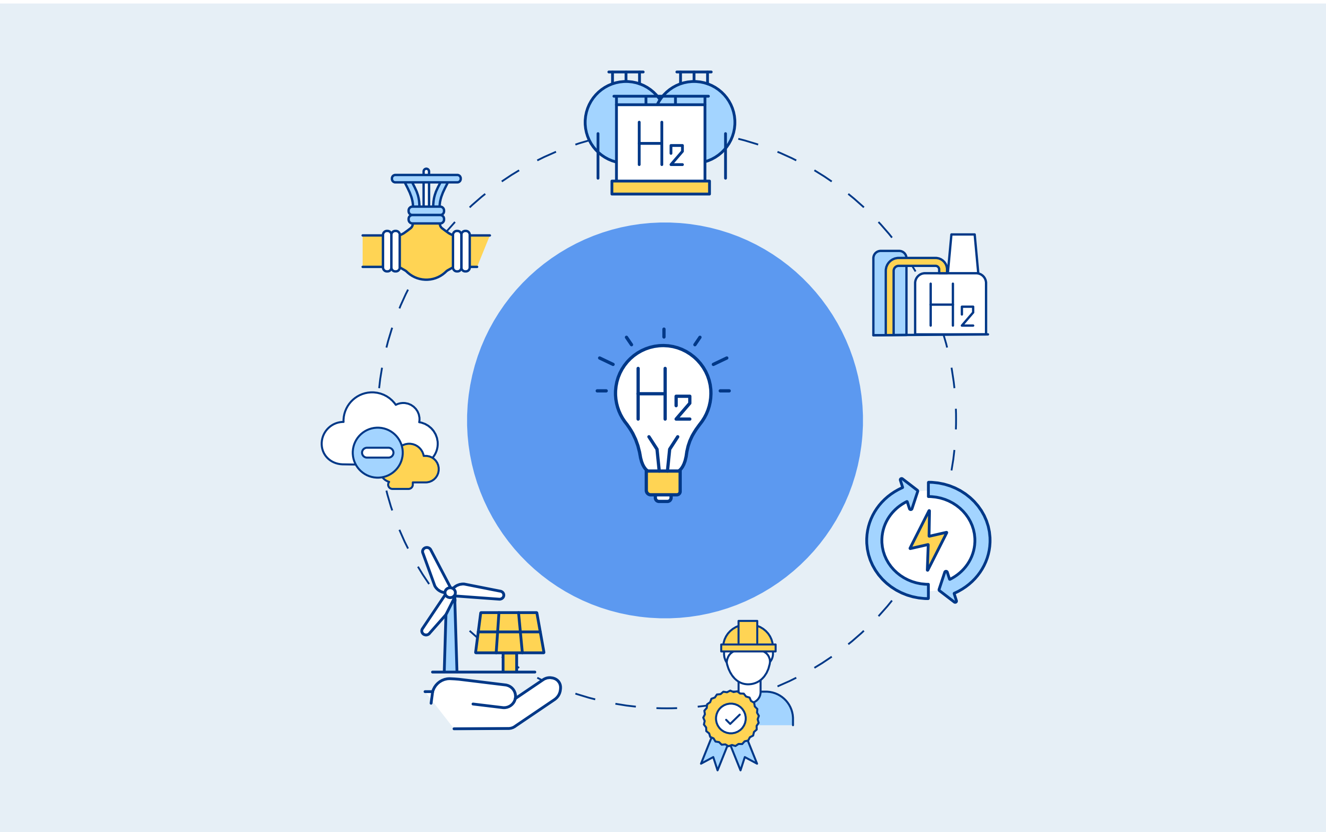
Introduction

The advent of green hydrogen in Mexico could set the ground for new business opportunities and a large potential for decarbonization for state-owned Petróleos Mexicanos (PEMEX) and Comisión Federal de Electricidad (CFE), which could become major players in the green hydrogen economy in Mexico.

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 or grey 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.

PEMEX is already the largest producer and consumer of hydrogen in the country, accounting for over 98% of the national demand. Locally produced green hydrogen could be introduced to decarbonize its refining and ammonia production processes, which currently consume over 200 thousand tons of fossil-based hydrogen per year. Synthetic fuels, produced with electrolytic hydrogen and captured CO_2, could replace current fuel refining and imports for different end uses contributing to a lower carbon and more nationally sovereign fuel mix. For CFE, opportunities in green hydrogen could arise in the reconversion of its thermal power plants to run entirely or partially on green hydrogen and through the injection of hydrogen into the gas network to either supply or consume a lower-carbon gas and hydrogen blend.

The objective of this report is not to provide recommendations on the companies' business but rather to present the potential opportunities in green hydrogen for PEMEX and CFE giving an estimated hydrogen demand and cost curves for five key areas of application: refining, ammonia production, synthetic fuels, injection into the gas network, and combustion in thermal power plants.



2. Methodology

Green hydrogen demand projections and economic analysis were developed for each of the target segments to reach a quantified vision of the opportunities for PEMEX and CFE up to 2050. Figures of merit were defined using industry interviews, bibliographic reviews, and the authors' technical and commercial expertise in green hydrogen as inputs. The data used from PEMEX and CFE was consulted from publicly available documents and websites. The figures of merit are specific for each application, and include, for example, the technical limits for injection of hydrogen into the natural gas pipelines, current hydrogen demand in refineries, and the requirement of energy storage to integrate large quantities of renewable energy into the power grid. Two realistic green hydrogen demand projections are presented: one based on conservative assumptions, named 'NDC Compliance', and one with a more favorable hydrogen deployment scenario, named 'Hydrogen Breakthrough'.

Cost estimations and comparisons with the hydrogen alternative were made for each segment. The required levelized cost of hydrogen (LCOH) was calculated using Hinicio models to compare its economic competitiveness against the conventional technology for each of the applications. The analysis considered three different time horizons in 2020, 2030, and 2050, and yielded the target LCOH for each application. LCOH projections were made towards 2050 to identify the expected time for cost parity for the grey hydrogen alternative, i.e., the projected LCOH vs the target LCOH.

The inputs for these projections of cost evolution of hydrogen include the current and historical prices of the alternatives, such as diesel and natural gas, as well as projections in the green hydrogen infrastructure throughout its value chain, including electrolyser efficiency and lifetime, capital and operating expenses, costs of renewable energy, etc. The results of this cost projections yield estimated points in time for cost-parity of hydrogen against the conventional alternative, providing a time frame in which green hydrogen demand is expected to rise for each application.

2.1 Hydrogen demand scenarios

The NDC Compliance scenario is based on the assumption that Mexico will fulfill its climate commitments to comply with the Paris Agreement according to the Nationally Determined Contributions (NDCs) it submitted in 2015. This scenario considers the country adopts new technologies for decarbonization in the targeted sectors, where hydrogen plays a moderate role, according to its cost competitiveness. Its objective is to provide a realistic framework of reference for the projection of the hydrogen market share, assuming the country will reach its target NDCs by 2030 and 2050, a commitment Mexico reiterated at the COP 25 in late 2019 and updated in December 2020[2]. The NDCs state a commitment to make a reduction of 22% greenhouse gas emissions (GHG) by 2030, compared to a projected baseline. NDCs are disaggregated by segment, with transport being the most relevant for this study with a GHG reduction commitment of 18%, power generation with 31%, residential and commercial with 18%, oil and gas with 14%, and industry with 5%, as it can be observed on Table 2-1.

2. SEMARNAT, Mexico's Nationally Determined Contributions – 2020 Update.

Table 2-1. Mexico's NDC commitments for GHG reductions by segment to 2030[3].

	Projected BAU ($MtCO_2e$)	Projected NDC ($MtCO_2e$)	Committed GHG Reduction
Transport	266	218	18%
Electricity Generation	202	139	31%
Residential and commercial	28	23	18%
Oil and gas	137	118	14%
Industry	165	157	5%
Agriculture and livestock	93	86	8%
Waste	49	35	29%
LULUCF[4]	32	-14[5]	144%
Total	**972**	**762**	**22%**

The Hydrogen Breakthrough scenario makes more optimistic assumptions and considers that hydrogen has an accelerated evolution in costs and technology, with high industry adoption and intensive policy support worldwide and in Mexico, following the projections of the Hydrogen Council[6]. Its objective is to explore the largest potential market share of hydrogen technologies under realistic but favorable assumptions.

A series of assumptions were made to characterize each scenario with milestones in 2020, 2030, and 2050 across five themes: climate goals, sovereign energy transition, public and private investment, cost competitiveness, and technical development. The main characteristics and considerations used for each theme are summarized in Tables 2-2 to 2-6.

Table 2-2. Assumptions for green hydrogen scenarios in Decarbonization Goals.

Decarbonization goals	2020	2030	2050
NDC Compliance	Mexico is part of the Paris Agreement and reiterated its position to comply with its NDCs at the COP 25 in December 2019. Mexico's efforts to comply with the agreement do not yet consider the incorporation of green hydrogen technologies.	Mexico complies with its climate commitments for 2030. Green hydrogen has a market share according to its cost-competitiveness for each segment.	Mexico keeps fulfilling its climate commitments according to its NDCs. Green hydrogen technologies are part of the solutions to decarbonize the economy, with a market share corresponding to its cost-competitiveness.
Hydrogen Breakthrough	Mexico begins its efforts to adopt green hydrogen in late 2020 or early 2021 as a technology to support the compliance of its NDCs.	Mexico fulfills or exceeds its NDC-related goals. Green hydrogen is supported heavily in sectors that are difficult to decarbonize by other technologies.	Mexico remains in the Paris Accord and in the most ambitious global initiatives for carbon neutrality. Mexico becomes an important player in the development and manufacturing of components in the green hydrogen value chain.

3. Intended Nationally Determined Contribution of Mexico, 2015.
4. Land Use, Land-Use Change and Forestry.
5. Negative due to emissions absorptions.
6. The Hydrogen Council is a global initiative uniting CEOs of leading energy, transport and industry companies with a common vision and long-term ambition for hydrogen to foster the energy transition.

Table 2-3. Assumptions for green hydrogen scenarios in Sovereign Energy Transition.

Sovereign energy transition	2020	2030	2050
NDC Compliance	Mexico has a regulatory framework that supports continuous adoption of renewable energy.	Mexico complies with its climate and renewable energy commitments for 2030, favoring national production over energy imports.	Mexico has transitioned to a cleaner and more sovereign energy matrix, reducing the need for energy imports.
Hydrogen Breakthrough	Mexico includes green hydrogen in its regulatory framework as a decarbonization and energy vector.	The Mexican energy transition includes nationally produced green hydrogen, with growing but conservative market shares.	Mexico has significant advancements towards a highly renewable energy matrix with green hydrogen playing a key role in sector integration and decarbonization. Mexico comes closer to being energy self-sufficient.

Table 2-4. Assumptions for green hydrogen scenarios in Public and Private Investment.

Public and private investment	2020	2030	2050
NDC Compliance	Public and private actors make investments to reach Mexico's NDC. Investment is favored in mature and demonstrated technologies, developed in other countries.	Investment in decarbonization is maintained by public and private actors. Investments in green hydrogen are made in segments where it has become cost-competitive.	Mexico's investments in green hydrogen have increased since 2030, as it reaches cost parity in new segments.
Hydrogen Breakthrough	Public and private actors begin to plan investments in green hydrogen technologies that allow tests before they are fully competitive in the market.	The green hydrogen ecosystem in Mexico is maturing, with pilot projects in most segments. There is an early adoption of green hydrogen technologies as they reach cost parity.	Investments in green hydrogen have continued to rise from 2020 to 2050. Mexico has a mature green hydrogen market, covering the national demand and allowing some exports. Investments have allowed national value chains to develop, technology and create jobs.

Table 2-5. Assumptions for green hydrogen scenarios in Cost Competitiveness.

Cost competitiveness	2020	2030	2050
NDC Compliance	Green hydrogen is 100% competitive with other technologies in very few applications.	Green hydrogen has had a "Business as Usual" improvement in costs. Green hydrogen is 100% competitive for some niche applications.	Green H_2 maintains an improvement in prices until 2050, however other technologies do so as well, and as a consequence, it has moderate market-shares.
Hydrogen Breakthrough	Green hydrogen is 100% competitive compared with other technologies in very few applications.	The global push for green green hydrogen has resulted in accelerated cost declines that meet Hydrogen Council forecasts.	Hydrogen Council predictions for LCOH, competitiveness by application, market shares and global green hydrogen demand are met.

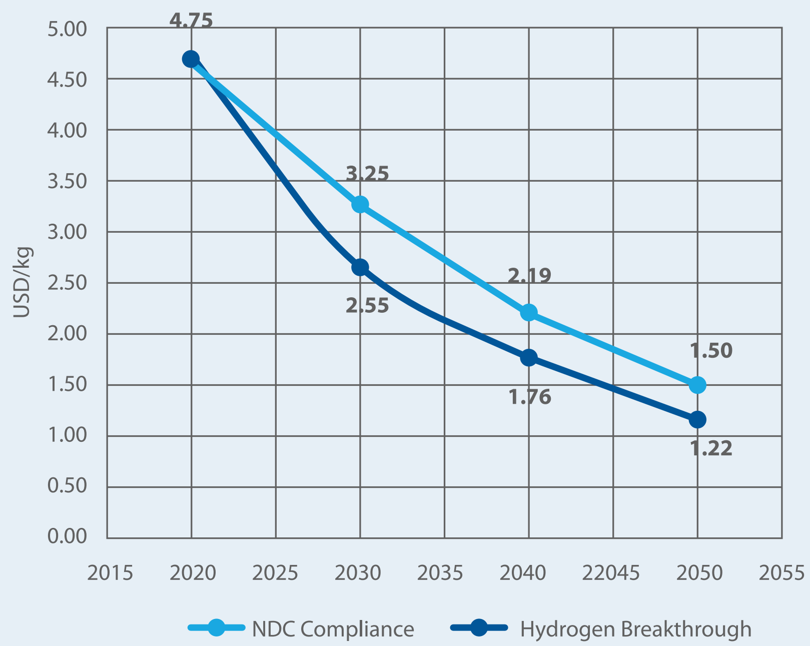
Table 2-6. Assumptions for green hydrogen scenarios in Technical Development.

Technical development	2020	2030	2050
NDC Compliance	Green hydrogen is emerging as a major industry integrator and improvements in technical performance are expected in nearly all applications.	Green hydrogen has modestly improved its performance under a BAU scenario.	Green hydrogen met only some of the performance improvement goals (DOE, IEA, IRENA, etc). Other clean technologies also improved their performance and took a significant market share per application.
Hydrogen Breakthrough	Green hydrogen is emerging as a major industry integrator and improvements in technical performance are expected in nearly all applications 2020.	Green hydrogen technologies have improved their technical indicators according to the projections of the most active energy agencies on the subject (DOE, IEA, etc.).	The global momentum for green hydrogen made the technological performance of green H_2 applications equal to or better than 2020 projections. Consequently, green hydrogen acquires market shares equal to or greater than those foreseen by the Hydrogen Council in 2020.

3. Projections of LCOH for green hydrogen

Cost projections for green hydrogen were made using Hinicio models for LCOH in Latin American countries and adapted to the Mexican context. The models consider technological factors such as electrolyser costs, efficiencies, water consumption, and lifetime, and those specific for the country, such as the renewable energy resource and estimated capacity factors, cost of electricity, and adjusted costs of installation and operation of the electrolysers. The main differences in the scenarios' assumptions for LCOH are either more conservative or more optimistic evolutions of electrolyser costs, efficiencies and lifetimes.

Figure 3-1. Projected LCOH for Green Hydrogen in 2020-2050.



Projected LCOHs for green hydrogen start both at 4.75 USD/kg in 2020. The NDC Compliance scenario yields LCOHs of 3.25 USD/kg in 2030 and 1.50 USD/kg in 2050, while in the Hydrogen Breakthrough they are of 2.55 USD/kg and 1.22 USD/kg, respectively.

The resulting cost curve for green hydrogen or LCOH evolution from 2020 to 2050 will then be compared to the target LCOH curve for each application to find the point of cost parity for both scenarios.

4. Opportunities for green hydrogen in refineries

Accounting for over 90% of PEMEX´s hydrogen consumption —and a slightly smaller share for the whole country—, oil refining processes in Mexico could become a major consumer of green hydrogen, posing substantial business opportunities and emissions reduction potential for the state-owned company and its affiliates. Hydrogen has been used in oil refining all around the world for decades in the hydrocracking and hydrogenation processes, to upgrade heavy hydrocarbon fractions by increasing the hydrogen to carbon ratio[7] and to remove sulfur and other impurities from diesel and gasolines[8].

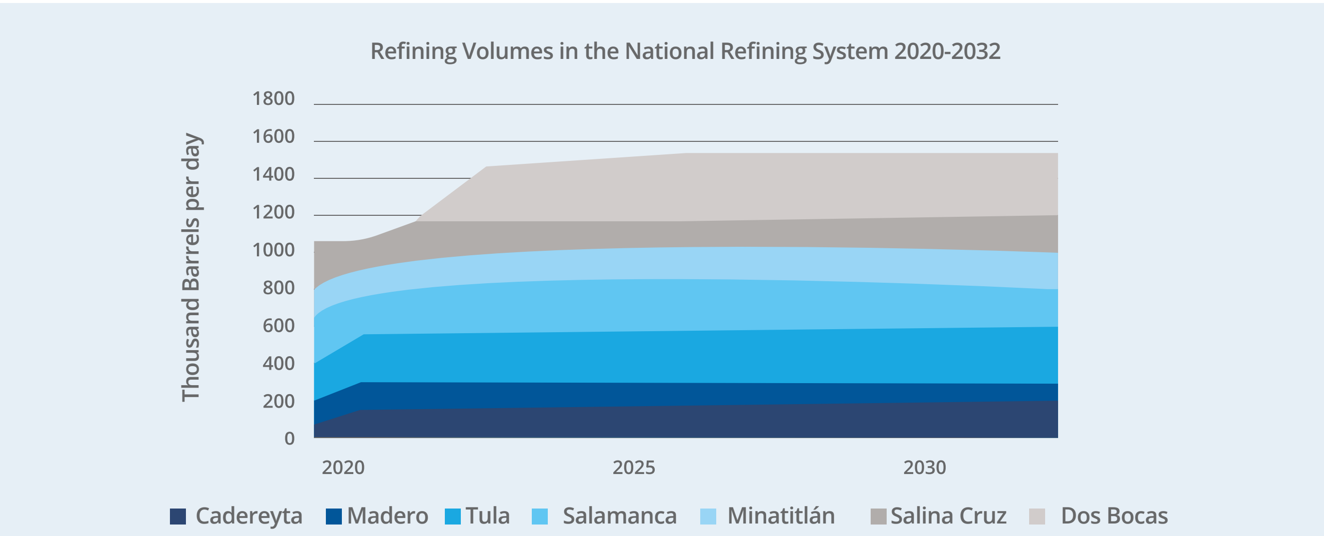
Hydrogen demand for PEMEX refineries was of 215 thousand tons per year in 2016, as reported by PEMEX[9], and distributed through its six refineries: Cadereyta, Madero, Minatitlan, Salamanca, Salina Cruz, and Tula. The production of hydrogen comes from two fossil-based and carbon-intensive processes: naphtha reforming, which is performed in all its refineries and accounts for 58% of the total, and steam methane reforming (SMR) of natural gas, which is performed in all refineries except for Tula and Salina Cruz, and accounts for the remaining 42% of the hydrogen produced.

4.1 Hydrogen demand in refineries to 2050

According to the national 'Crude Oil and Petroleum Products Prospective 2018-2032' published by the Ministry of Energy (SENER), refining volumes are expected to grow continuously until 2027, with processed volumes growing in all refineries and the entry into operations of the Dos Bocas Refinery in 2023 totaling to a rise in 50% of the total crude refined from around one million barrels in 2020 to 1.5 million in 2027.

Additional capacity or new refineries are not expected to come online after that year. The volume of hydrogen required for the refining process is related to the number barrels of crude oil refined, which means an increase of around 50% in the hydrogen demand for refineries can be expected from 2020 to 2027, while it will remain constant until 2050, regardless of the technology employed to produce the hydrogen. For refineries, the levelized cost of green hydrogen is compared with the cost of the conventional grey hydrogen supplied.

Figure 4-1. Projected refining volumes in the National Refining System for 2020-2032. (IMP[10])



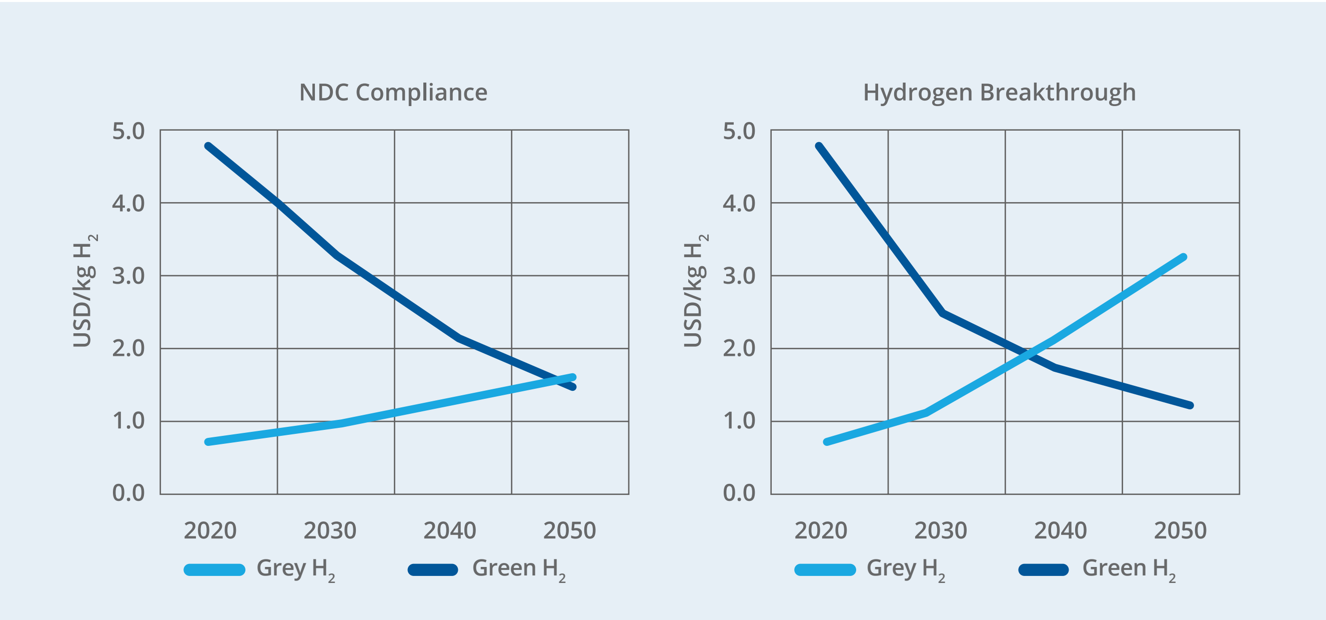
7. Bricker M., Hydrocracking in Petroleum Processing, 2014.
8. Energy Information Agency, Hydrogen for refineries is increasingly provided by industrial suppliers, 2016.
9. PEMEX, Suministro de Hidrógeno en refinería Miguel Hidalgo en Tula de Allende, Hidalgo, 2018.
10. IMP: Mexican Institute of Petroleum

4.2 Projected green hydrogen demand in refineries

According to Mexico's NDCs the emissions reduction target for the oil and gas sector is expected to be of 14%, relative to the projected baseline by 2030. To contribute to that goal, the NDC Compliance scenario considers a replacement of 1% of grey hydrogen with renewable hydrogen in refineries by that year. Meanwhile, other measures and technologies will reduce the remaining emissions to achieve the sector's target, such as efficiency improvements in downstream processes and carbon capture, use, and storage (CCUS). For the NDC Compliance scenario, the increase in the cost of the grey hydrogen supplied is based on the assumptions from SENER's prospective scenario with higher fuel cost increase for 2018-2032, which considers a moderate increase in the price of natural gas used to produce it.

The projections resulting from NDC Compliance assumptions show a slow increase over time in the cost of the fossil-based hydrogen supplied to the refineries which, compared to a conservative decline in the cost of green hydrogen, yield an estimated time of cost parity until 2048. The late competitiveness of green hydrogen would result in a relatively small demand from refineries by 2050. However, to comply with the NDC's emissions reduction target for the sector, green hydrogen is assumed to be introduced to replace 10% of PEMEX's total hydrogen demand by mid-century.

Figure 4-2. LCOH and target LCOH evolution for refineries in NDC Compliance and Hydrogen Breakthrough scenarios.



For the Hydrogen Breakthrough scenario, Mexico will have deployed green hydrogen pilots in refineries and a first wave of projects replacing up to 3% of the grey hydrogen demand in the National Refining System by 2030, driven by environmental goals and early adoption of green hydrogen solutions. The cost increase of grey hydrogen is steeper following the projected assumptions from SENER's energy planning prospective and a carbon price rising to 60 USD/ton by 2050. However, green hydrogen will not be at cost parity with its grey counterpart until 2038, after which an accelerated adoption is expected for the following twelve years until reaching a share of 50% of the hydrogen in the SNR by 2050, which would account for over 200 kilotons of green hydrogen per year, requiring an electrolyser installed capacity of 2,400 MW.

Figure 4-3. Projected green hydrogen demand in refineries from 2020 to 2050.

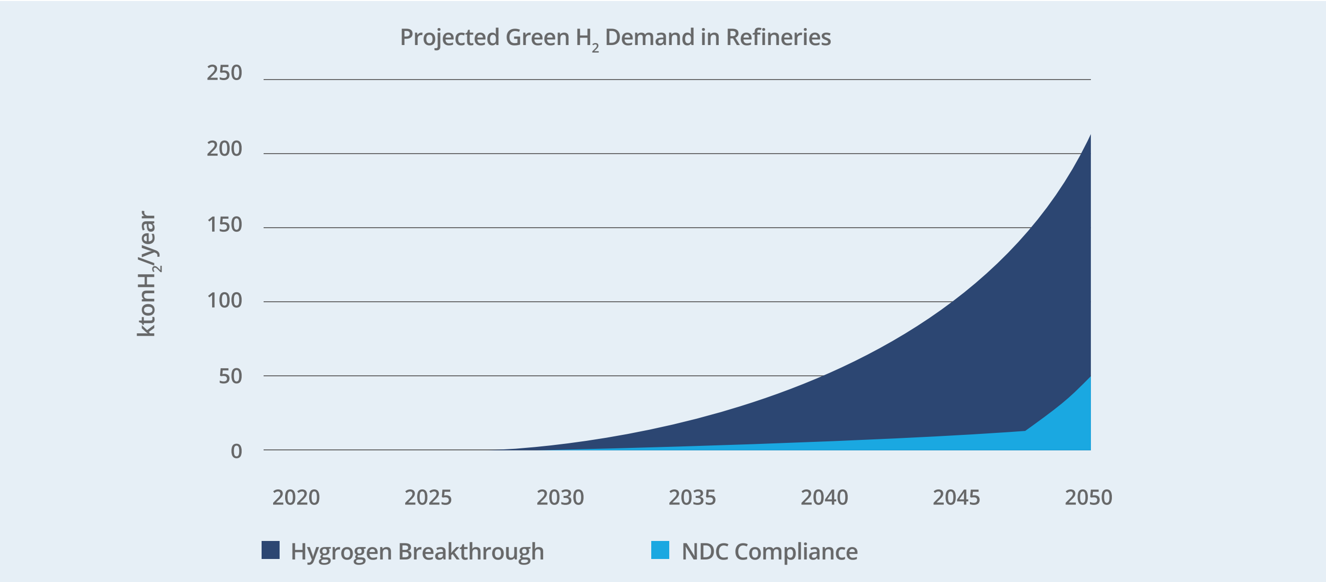
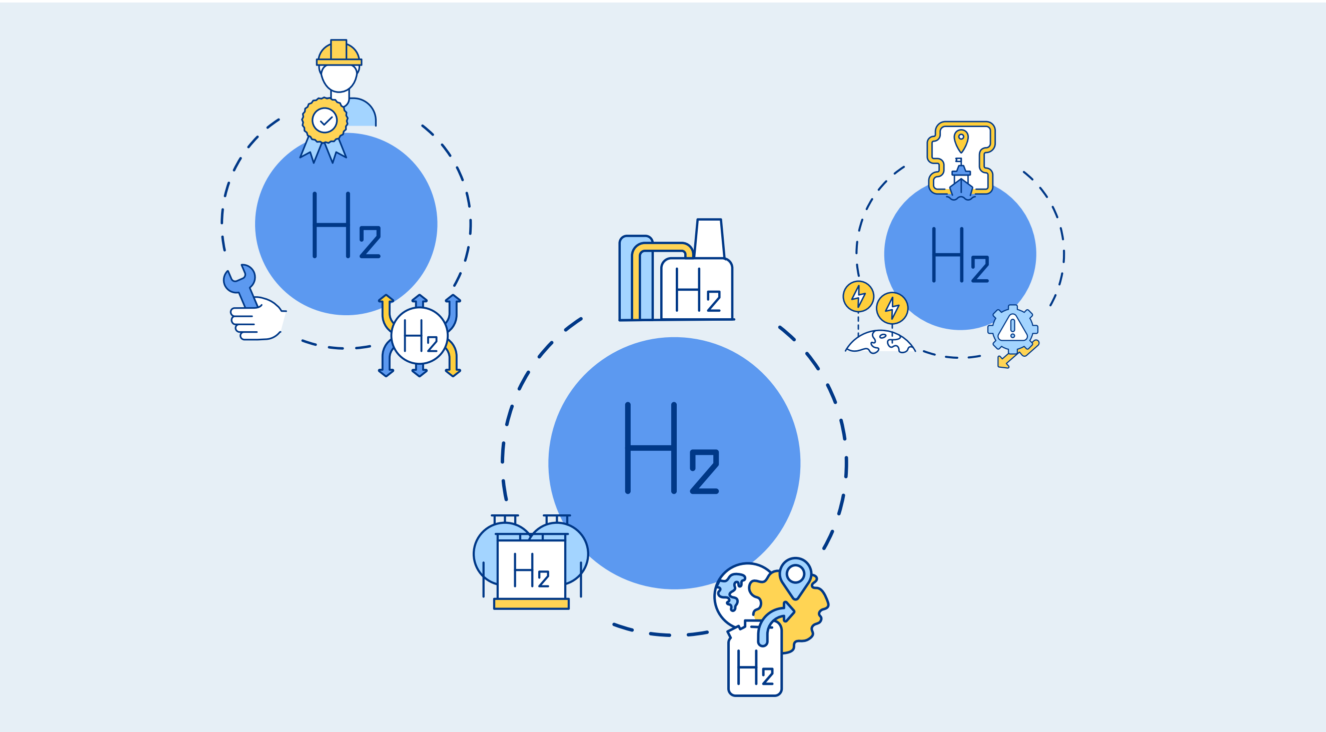


Table 4-1. Hydrogen demand and electrolyzer capacity for refineries in 2030 and 2050.

Refineries	Hydrogen Demand		Electrolysis Capacity	
	2030	2050	2030	2050
NDC Compliance	4 ktpa	40 ktpa	48 MW	480 MW
Hydrogen Breakthrough	12 ktpa	200+ ktpa	145 MW	2,400 MW



5. Opportunities for green hydrogen in ammonia production

The production of ammonia is the second largest consumer of hydrogen today. Ammonia is a compound of nitrogen and hydrogen (NH_3) used in the chemical industry, largely to produce fertilizers. In Mexico, PEMEX is the largest producer of ammonia, to which it destines under one tenth of its hydrogen production. Even if in 2019 PEMEX's ammonia production plants did not operate, a large potential for the introduction of green hydrogen towards 2050 exists.

5.1 Hydrogen demand for ammonia to 2050

Data from the National Chemical Association (ANIQ) shows that national ammonia production has been in decline for the last ten years, attributed to a lack of supply of natural gas to the Cosoleacaque plant down to halting production in 2019. To compensate for that decline, rising imports have come, although overall ammonia consumption in the country decreased by around 25% in the same decade[11]. To quantify business opportunities in green ammonia, i.e., ammonia produced using green hydrogen, production is assumed to rise again in the same rate as the previous decade's decline up to 2031, when it is expected to reach its 2010 levels. From then on, a 1% annual growth rate is considered, as projected globally by the International Fertilizer Association. With PEMEX being the sole major producer of ammonia in Mexico, these changes in ammonia consumption are expected to drive proportional changes in the hydrogen demand, going from 100,000 tons per year in 2020 to over 230,000 tons in 2050.

5.2 Projected green hydrogen demand for ammonia

Green hydrogen consumption for ammonia production is assumed to be driven by environmental and self-sufficiency goals as a share of the total hydrogen demand.

In the NDC Compliance scenario, cost parity of green ammonia is not expected until close to 2050 and no production is foreseen by 2030. The stated contribution to the NDCs by the industrial sector is of 5% by 2030, however green ammonia is not expected to be part of it. A slow adoption of green ammonia is expected starting in 2038, when PEMEX hydrogen supply contracts in refineries are due to be finished and new technological outlook would be evaluated.

By 2050, green ammonia production will have only been economically competitive with the conventional for a few years, and an adoption of 10% of green hydrogen is assumed for national ammonia production, requiring an installed capacity of 270 MW of electrolysis to produce the 24 ton per year this represents.

The Hydrogen Breakthrough scenario is placed in a context of favorable global and Latin American ecosystems in which green ammonia is beginning to be adopted. Mexico proposes its pilot project for producing green ammonia with 80 MW of electrolysis that could substitute up to 5% of the national hydrogen demand for ammonia production, which is much more conservative than the European Hydrogen Roadmap's goal to produce one third of its ammonia with ultra-low carbon hydrogen by 2030[12].

[11]. SENER, Crude Oil and Petroleum Products Prospective 2018-2032.
[12]. Fuel Cells and Hydrogen Joint Undertaking, Hydrogen Roadmap Europe, 2019.

Figure 5-1. LCOH and target LCOH evolution for ammonia in NDC Compliance and Hydrogen Breakthrough scenarios.

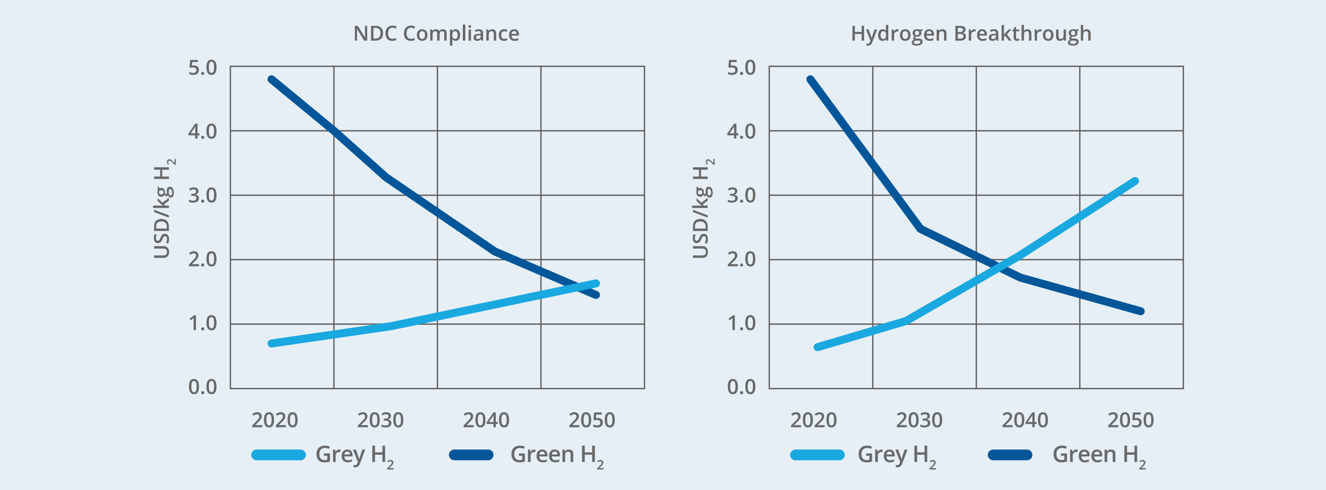
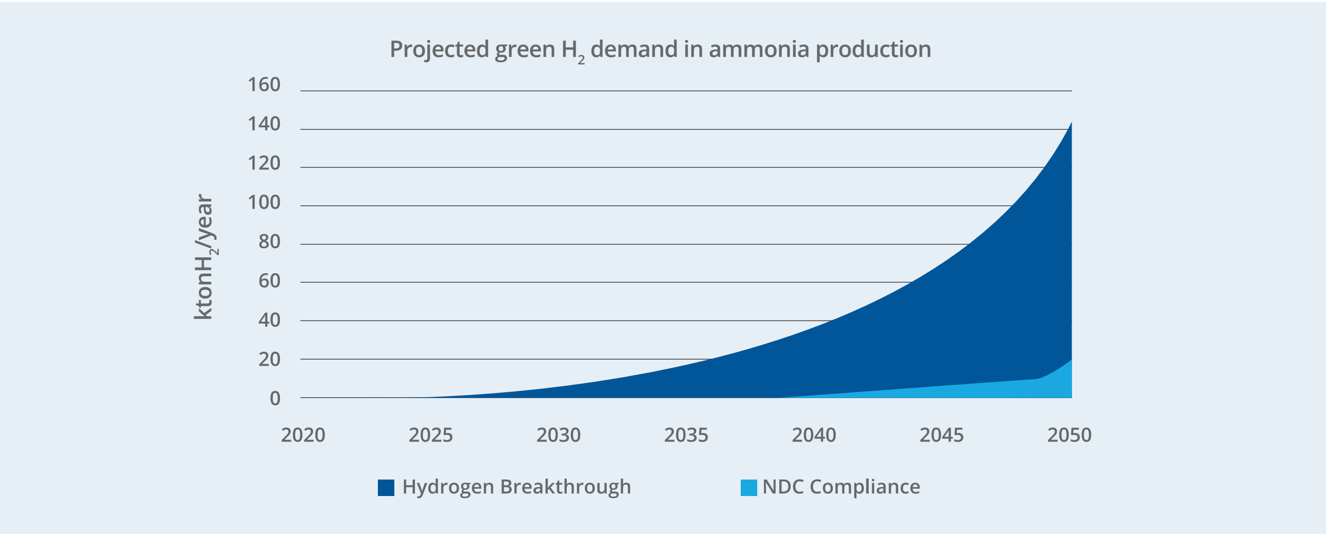


Figure 5-2. Projected green hydrogen demand for ammonia production from 2020 to 2050.



Cost parity is expected to come in 2038. After more than a decade of full economic competitiveness, by 2050 Mexico could satisfy up to 60% of the country's ammonia demand through Power To Ammonia, requiring more than 1,600 MW of electrolysis capacity to produce 140 kilotons of green hydrogen per year, equivalent to two of Chile's HyEx projects, currently the world's largest green ammonia production plan; or around half of the Chilean National Green Hydrogen Strategy's goal for 2030.

Table 5-1. Hydrogen demand and electrolyser capacity for ammonia in 2030 and 2050.

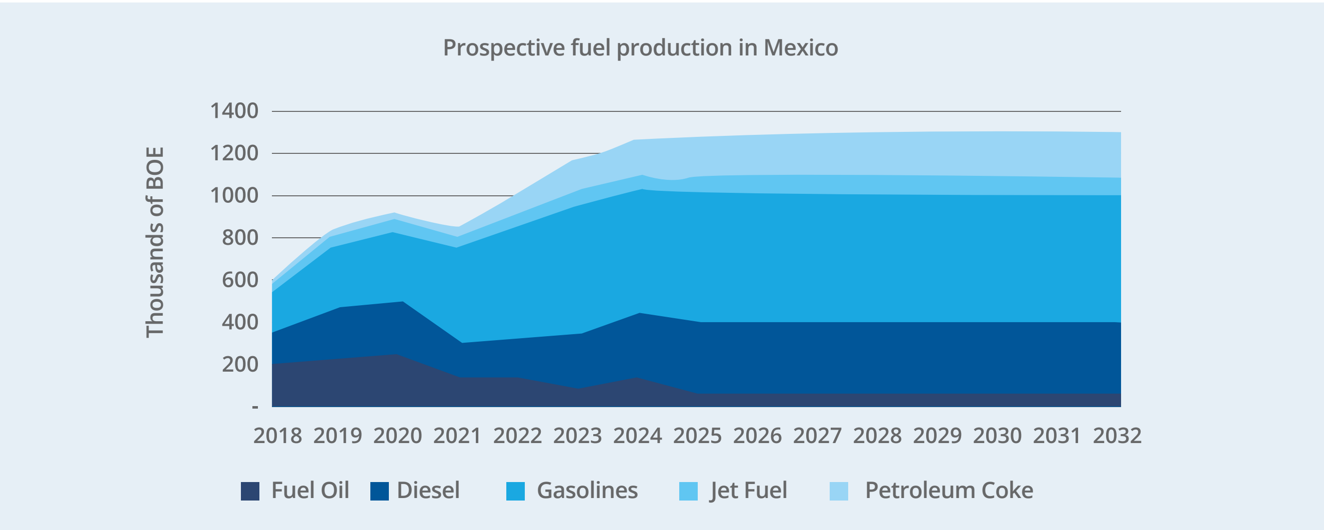
Ammonia	Hydrogen Demand		Electrolysis Capacity	
	2030	2050	2030	2050
NDC Compliance	0 ktpa	24 ktpa	0 MW	270 MW
Hydrogen Breakthrough	7 ktpa	140 ktpa	85 MW	1,650 MW

6. Opportunities for green hydrogen for synthetic fuels

Synthetic fuels, also known as e-fuels or syn-fuels, are produced using green hydrogen and captured CO_2, which results in a low carbon alternative to conventional fuels that can be used without major changes in infrastructure and equipment for its combustion. This allows for direct substitution of fossil fuels, thus addressing the same markets and applications.

Mexico currently produces fossil-based fuels making use of all refineries in the National Refining System, with Salina Cruz, Salamanca, Tula, and Cadereyta being the major producing units. The largest production corresponds to fuel oil, followed by gasolines and diesel, and moderate amounts of jet fuel and petroleum coke. SENER's prospective production for 2018-2022 shows an expected decline in the production of fuel oil, and an increase in output of all other fuels up to 2027, after when it is projected to remain constant, as seen in Figure 6-1.

Figure 6-1. Prospective fuel production in Mexico for 2018-2032[13].



For synthetic fuels, the target segment of interest considered in this report is aviation, where they could substitute conventional jet fuel, and are seen as a major potential vector for decarbonization. For road transportation, the use of synthetic fuels seems unlikely with the current transition to electrification, and where the use of hydrogen is expected to be in fuel cell powered vehicles. Fuel cells are also expected to be the dominant hydrogen-based energy source in industry, rail, and maritime transportation, not requiring e-fuels.

6.1 Hydrogen demand for synthetic fuels to 2050

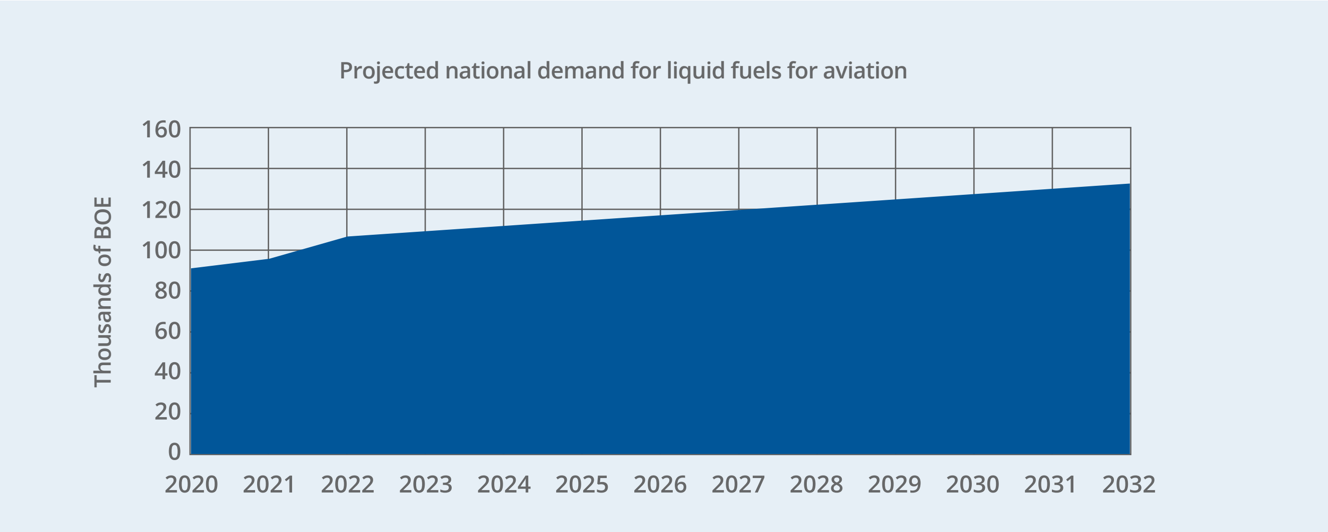
Under current governmental planning, Mexico fuel production is expected to rise to more than double the capacity in the period between 2018 and 2024, with a increasing output in all refineries, notably Madero, with a five-fold output increase, and the projected entry into operations of Dos Bocas in 2023. However, in this context, no hydrogen demand is expected for the production of synthetic fuels focusing solely on the

13. BOE: Barrels of Oil Equivalent.

refining of hydrocarbons. Thus, grey hydrogen demand for the refining process can be considered as a reference for fuel production, as detailed in Chapter 4.

A more reasonable analysis would be to project the consumption of fossil fuels in the segment of interest and directly compare costs and demand with synthetic fuel, rather than the hydrogen used to produce it. The projected demand for jet fuel for the aviation industry, which could potentially be substituted by green hydrogen, is shown in Figure 6-2 in barrels of oil equivalent (BOE), i.e., energy units.

Figure 6-2. Projected national demand for liquid fuels in the aviation sector.



6.2 Projected green hydrogen demand for Synthetic Fuels

In the NDC Compliance Scenario, there is no penetration of synthetic fuels expected in Mexico by 2030, given unfavorable cost projections and a lack of other driving factors for its adoption. Mexico's NDCs for transportation commit an emissions reduction of 18% compared to the 2030 baseline, but compliance would be achieved through other measures, such as improved vehicle performance, the use of fuels with lower carbon content, and electrification of light transportation.

By 2050, e-fuels will be an alternative still reserved solely for aviation, a sector with a strong mandate to decarbonize, but difficult to electrify or migrate to other new technologies. Within the aviation fuels segment, e-fuels will share the market together with biofuels and fossil fuels. Due to their low economic competitiveness, synthetic fuels will have no more than a 10% share of the aviation sector, for which under a thousand tons of hydrogen will be demanded per year, requiring less than 10 MW of electrolysis capacity.

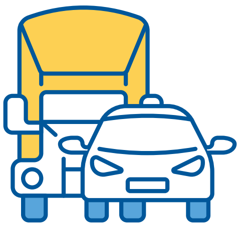
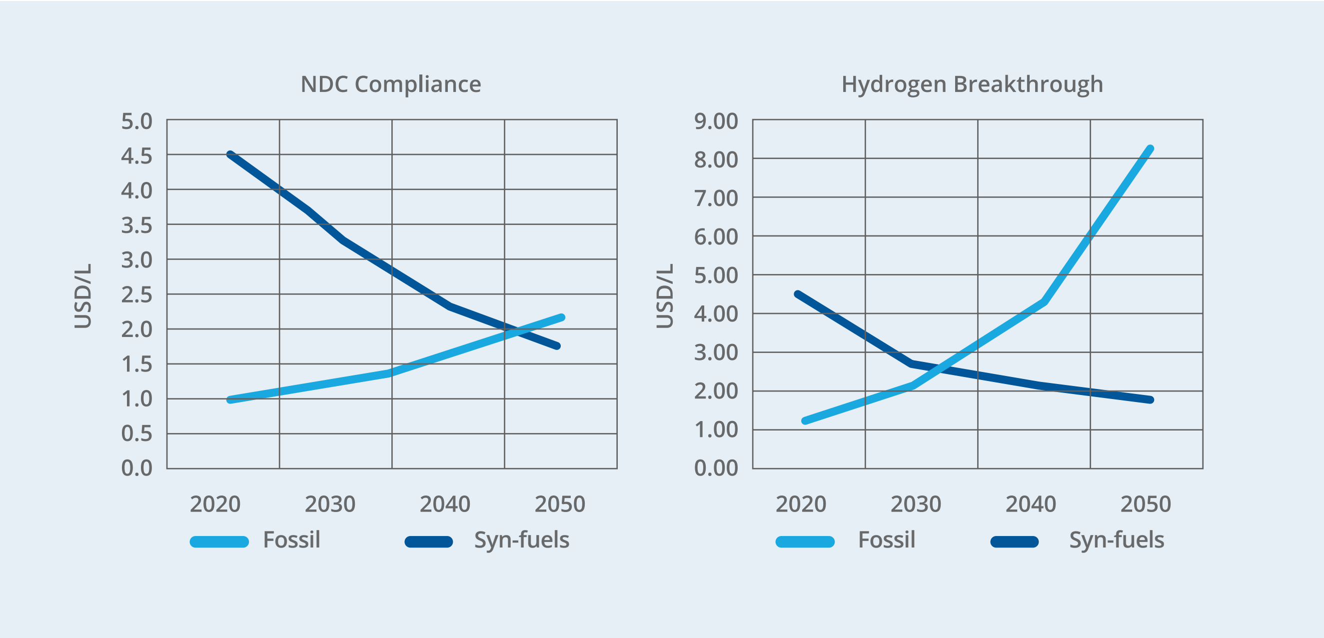
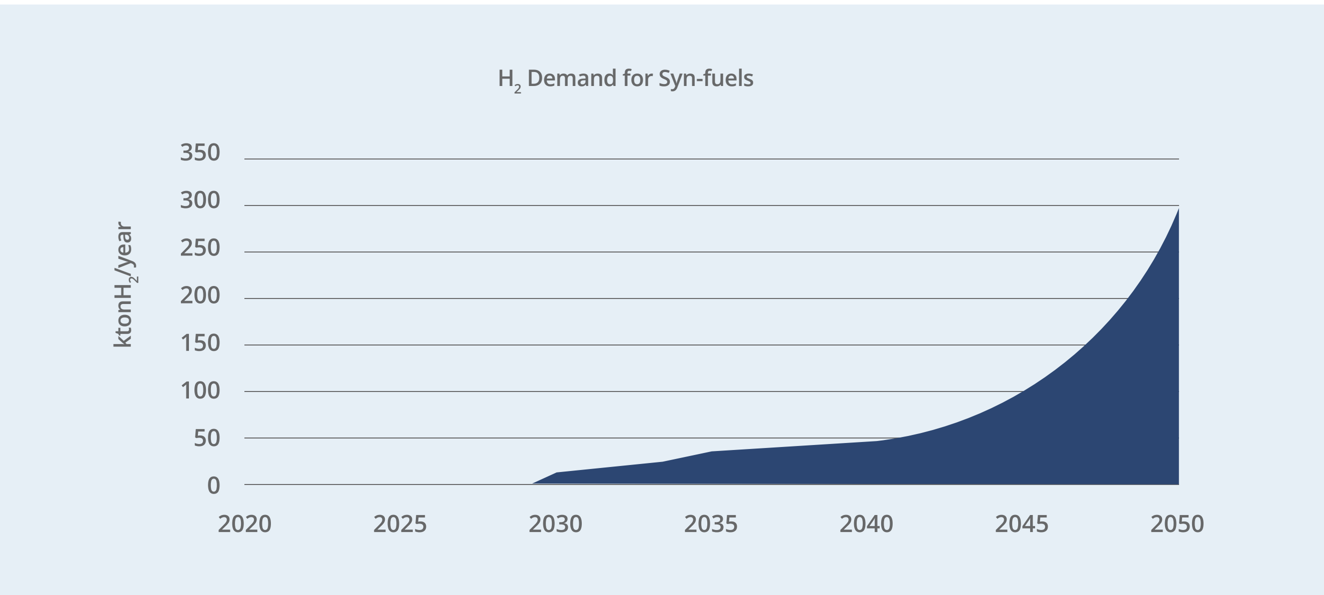



Figure 6-3. Projected costs of fossil fuels vs synthetic fuels in NDC Compliance and Hydrogen Breakthrough scenarios.



In the Hydrogen Breakthrough scenario, the prices of fossil fuels follow an increase as projected in SENER's 2018-2032 prospective for high costs, while synthetic fuels are expected to decrease their costs rapidly. Plans for pilot projects could be seen as early as 2024, leading to the production of over 40,000 tons of e-fuels annually by 2030 to substitute 0.6% of the aviation demand even before reaching cost parity which is projected to happen until 2035.

Figure 6-4. Projected hydrogen demand for synthetic fuel production in Hydrogen Breakthrough scenario, production in NDC Compliance scenario is negligible.



By 2050, fifteen years will have passed after achieving economic competitiveness with fossil fuels, and e-fuels will have experienced a broad deployment, being involved in aviation, maritime transport, rail, and even some industrial applications. Over 3,500 MW of electrolysis are expected to be installed, producing more than 300,000 tons of hydrogen per year and substituting roughly 9,200 BOE, corresponding to 12% of the forecasted demand in the aviation sector. In this scenario, Mexico's climate goals should require a reduction of emissions from the transportation sector by 36% by mid-century, with an expected contribution from e-fuels of up one third of that goal, coming mainly from the aviation segment.

Table 6-1. Hydrogen demand and electrolyser capacity for synthetic fuels in 2030 and 2050.

Syn-fuels	Hydrogen Demand		Electrolysis Capacity	
	2030	2050	2030	2050
NDC Compliance	0 ktpa	<1 ktpa	0 MW	270 MW
Hydrogen Breakthrough	10 ktpa	More than 300 ktpa	<10 MW	3,500+ MW

7. Opportunities for green hydrogen in the gas infrastructure

The use of hydrogen in the natural gas infrastructure has two alternatives: the production of synthetic methane and the injection of natural gas and hydrogen mix into the grid.

The production of synthetic methane using electrolytic hydrogen and captured CO_2, also known as methanation, results in a carbon-neutral gas identical in composition to fossil-based methane. The synthesis process has efficiency challenges to overcome, but could provide an alternative to decarbonize natural gas end uses by direct substitution without major changes in infrastructure, opening up the possibility for a large potential demand of a green hydrogen-based fuel, ready to be deployed at a large scale. However, the blending of green hydrogen with natural gas is seen as the alternative with major potential for hydrogen use in the gas infrastructure given the technical challenges remaining for methanation.

Green hydrogen can be mixed with conventional natural gas and then injected into the gas infrastructure. Injection of this blend into the grid has technical limitations that increase as the concentration of hydrogen rises, both on the supplier and the consumer sides. End uses of natural gas as a chemical feedstock have a low tolerance to changes in composition, allowing as little as 2% of hydrogen in volume in the mix, and uses of the gas blend for energy generation in thermal power plants can face challenges at a concentration of 20%.

From the gas infrastructure perspective, there are also constraints related to gas leakage and structural properties of the pipeline that start at a concentration of 10%. To cope with this limitations, regulations have been set in countries advancing the injection of hydrogen in the grid to stablish a limit of hydrogen volume in the mix, ranging from 0.02% in the Netherlands or 0.1% in Belgium and the UK to 6% of hydrogen allowed in the gas network in France and 10 % in Germany.

7.1 Hydrogen demand for the gas infrastructure to 2050

According to SENER's planning prospective, natural gas demand in Mexico is expected to rise for the next decade in varying yearly rates, with an overall growth of 17% for the 2020-2030 period going from around 8,300 to 9,700 million standard cubic feet per day (MMSCFD). Projecting a steady growth rate in the same trend, but slightly decreasing towards 2050, natural gas demand in Mexico would reach 10,900 MMSCFD in 2040 and nearly 12,200 by 2050 corresponding to a growth of 31% and 46% relative to 2020, respectively, as shown in Figure 7-1.

There is no current demand for hydrogen in the gas infrastructure in Mexico, although potentially up to a fifth of its natural gas consumption could be substituted by green hydrogen blended in the mix for gas with a lower carbon content once technological and regulatory measures are in place.

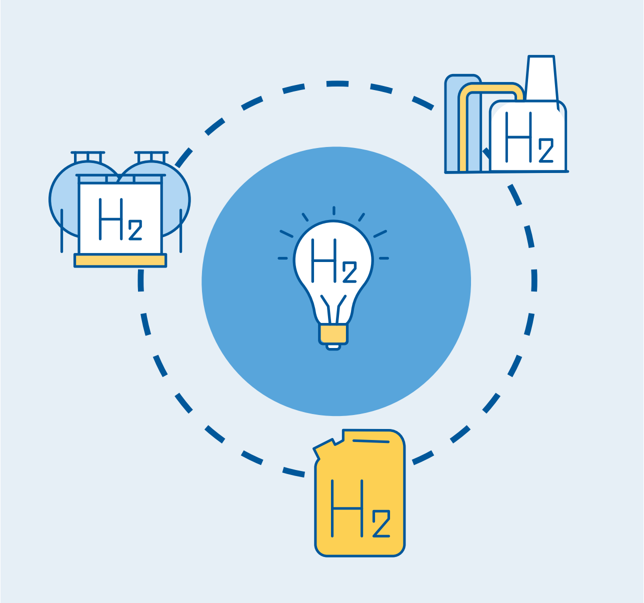
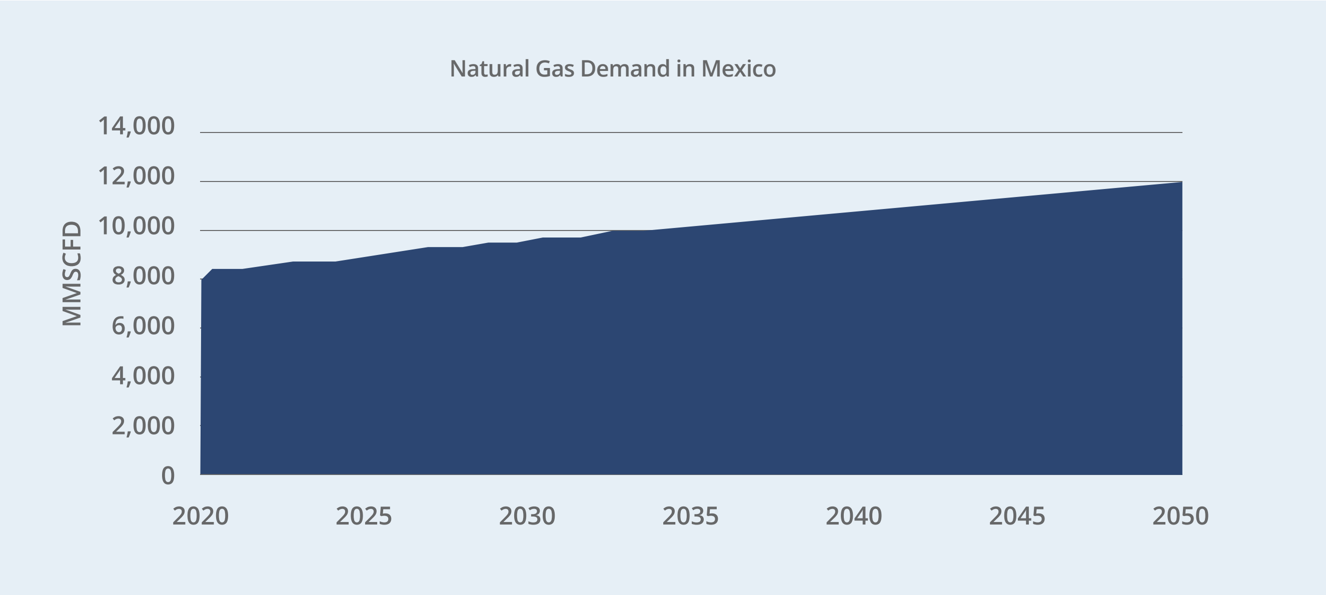


Figure 7.1. Prospective and projected natural gas demand in Mexico from 2020 to 2050.



7.2 Projected green hydrogen demand for the gas infrastructure

The prospect of substituting even a small share with green hydrogen could lead to the development of thousands of megawatts of electrolysis in the country.

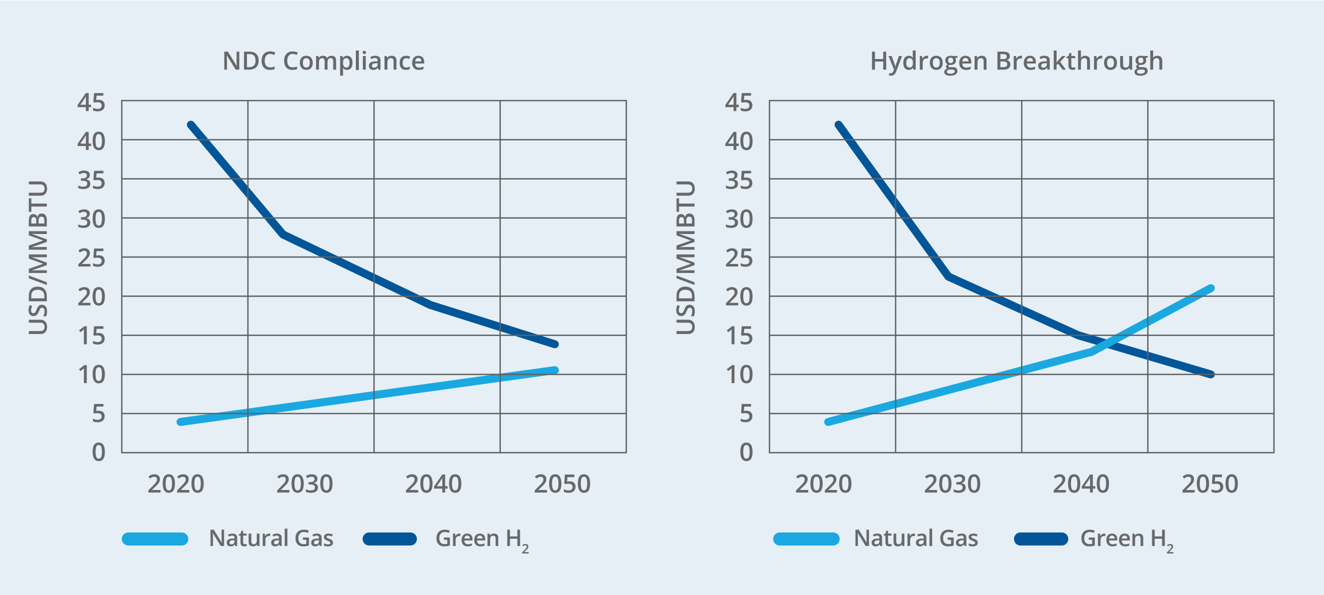
However, technical maturity and a considerable reduction in costs of producing green hydrogen are required for it to be directly competitive with natural gas. Unlike other applications, such as for refining and producing ammonia, where natural gas is also a feedstock in the process, for injection in the gas grid, the comparison is head to head in the cost of energy delivered by each fuel. This makes the competitiveness gap more challenging to reach, starting at around 10 times higher cost in both scenarios 2020 and is not even reached by 2050 in the more conservative projection.

In the NDC Compliance scenario hydrogen will still be 4.6 times more costly than natural gas, and only pilot projects with minor hydrogen production are foreseen by the time driven by climate commitments with under 10 MW of electrolysers installed. Compliance with Mexico's NDCs in the sectors where natural gas has presence will be addressed by other technologies such as renewable energy and CCUS in industry and power generation.

The slow growth rate will result in an output of under one kiloton per year until 2035, reaching 2 kilotons in 2040 and slightly accelerating deployment in that decade, as the competitiveness gap narrows, reaching up to 8 kilotons per year and 90 MW of electrolysis by 2050.

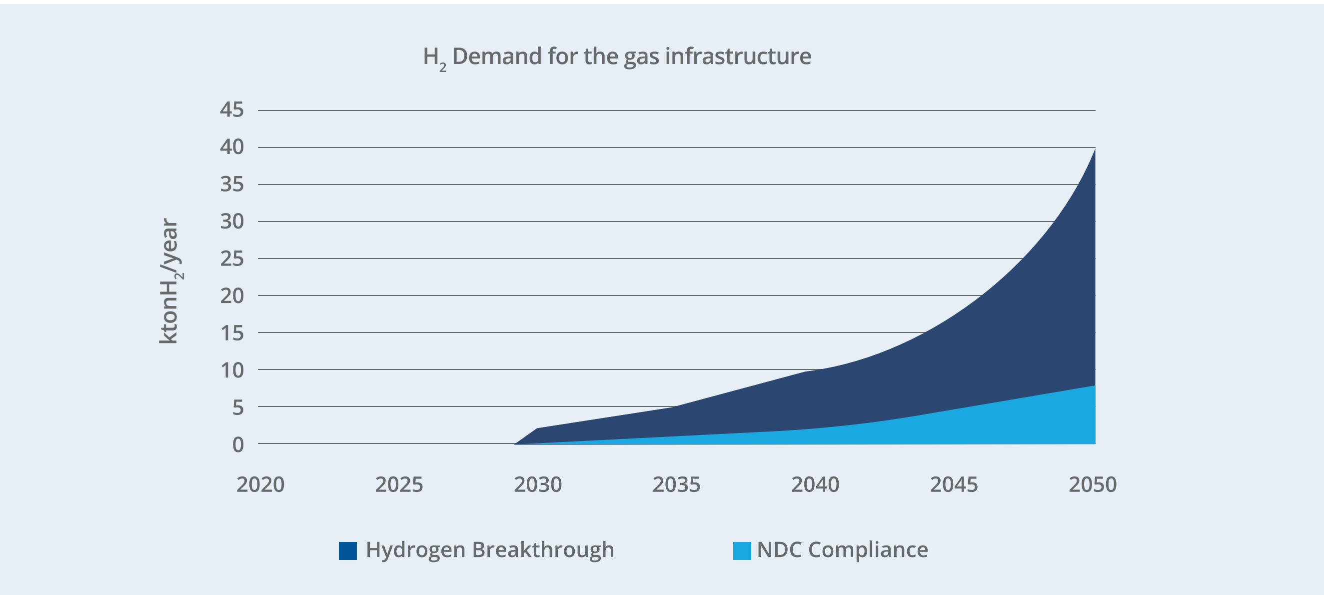
By mid-century, the economic competitiveness of green hydrogen as a fuel will have remained low compared to natural gas, not having achieved cost parity by then, and injection of hydrogen into the natural gas grid will be limited to specific segments of the national natural gas transport system, favored in regions with high renewable energy potential, high cost or low supply of natural gas, and strong environmental commitments.

Figure 7-2. Projected costs of equivalent energy of natural gas vs green hydrogen in NDC Compliance and Hydrogen Breakthrough scenarios.



The Hydrogen Breakthrough scenario shows a more promising reduction of competitiveness gap, with green hydrogen being 2.5 times more expensive to natural gas in 2030, comparable with its competitiveness at the time of writing of this report. A more aggressive deployment of pilot projects could take place for the injection of nearly three kilotons of hydrogen by then, accumulating more than 35 MW of electrolysis nation-wide. The injection volumes will not exceed 10% in each of the tested pipelines following the most permitting regulations worldwide of 2020.

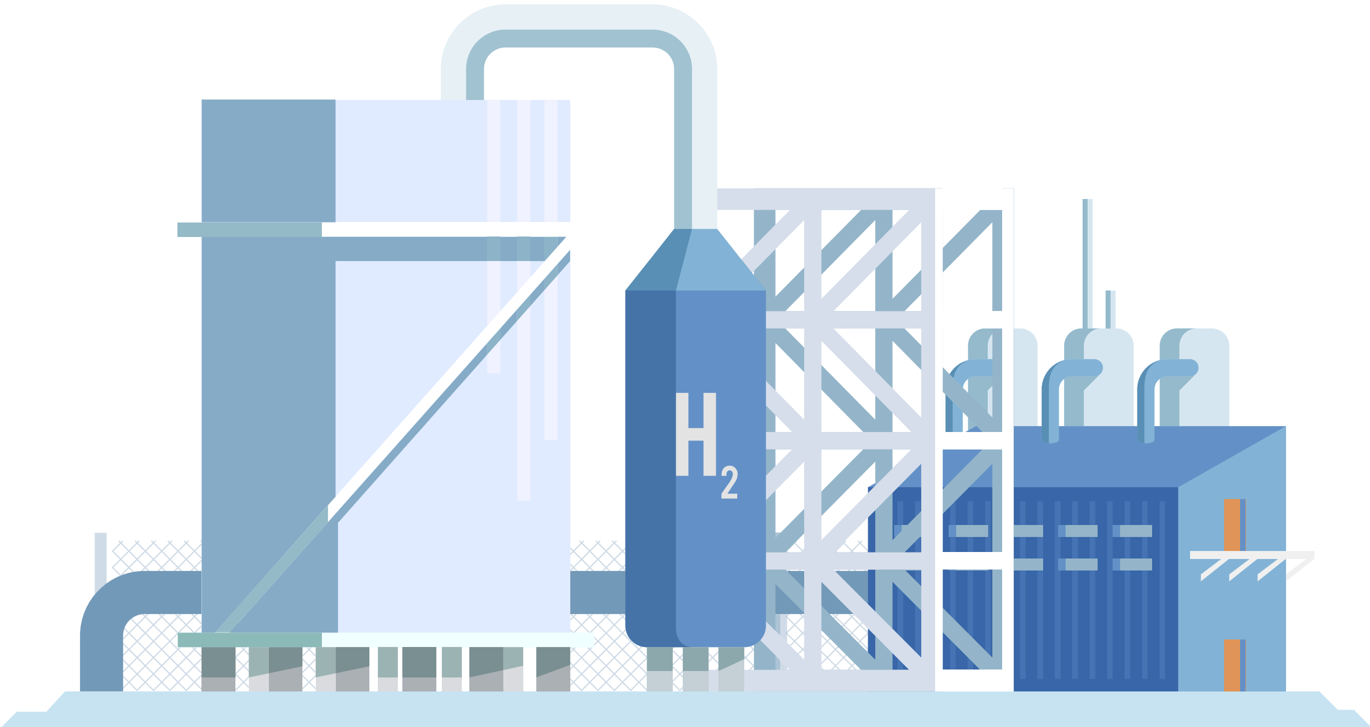
Figure 7-3. Projected hydrogen demand for the gas infrastructure in NDC Compliance and Hydrogen Breakthrough scenario.



By 2040, hydrogen demand from the gas infrastructure will surpass 10 kilotons per year and is expected to reach cost parity one or two years later. This will enable an accelerated growth of the volumes injected, growing four-fold to reach 40 kilotons per year in 2050 and a capacity of electrolysers installed of more than 460 MW. This will be driven by the evolution of hydrogen technology and will see a higher deployment in regions with high renewable potential and difficult access to natural gas.

Table 7-1. Hydrogen demand and electrolyser capacity for the gas network in 2030 and 2050.

Gas Infrastructure	Hydrogen Demand		Electrolysis Capacity	
	2030	2050	2030	2050
NDC Compliance	<1 ktpa	8 ktpa	<10 MW	90 MW
Hydrogen Breakthrough	3 ktpa	40 ktpa	35 MW	460 MW



8. Opportunities for green hydrogen in thermal power plants

Hydrogen can be used for direct combustion in reconverted or dedicated hydrogen power turbines for power generation as an alternative to fuel cells, which is of interest in this report for large-scale facilities owned by CFE. Some of the advantages over fuel cells include a lower investment cost, leveraging on existing infrastructure, more accessible maintenance being based on a well-known technology, and lower sensitivity to the quality of the hydrogen supplied. Additionally, the use of hydrogen in turbines could be part of energy storage systems that convert excess energy into hydrogen by electrolysis and then reconvert it back to energy in the turbine when needed.

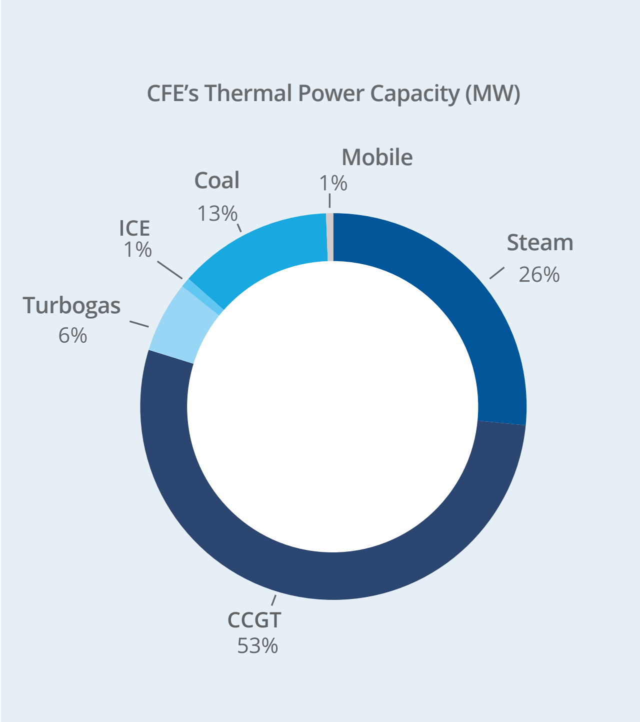
Currently, there are existing turbine models that can already run with hydrogen concentrations from 50-70% of hydrogen operating, for example, in refineries in Asia and Europe. Companies like GE, Mitsubishi, and Siemens are developing turbines that could run entirely on hydrogen, with expectancies of the first models to come online by 2030.

The retrofit, reconversion, and installation of partially or fully hydrogen fueled thermal power plants by CFE could provide an alternative to decarbonize the power currently produced in its natural gas-fueled turbines, and a cost-saving measure once green hydrogen becomes more competitive than its fossil counterpart on an energy content basis.

8.1 Hydrogen demand for to 2050

Up until the end of 2019, CFE had a reported installed capacity of over 41,000 MW of thermal power plants with a mix of conventional gas or fuel oil steam plants, combined cycle gas turbines (CCGT), turbogas units, internal combustion engines (ICE), coal power, and mobile units. Focus will be put on CCGTs, for which the most plants are expected to be added or reconditioned, where the highest development of hydrogen turbines is foreseen and which account for over half of the capacity and power generated by CFE.

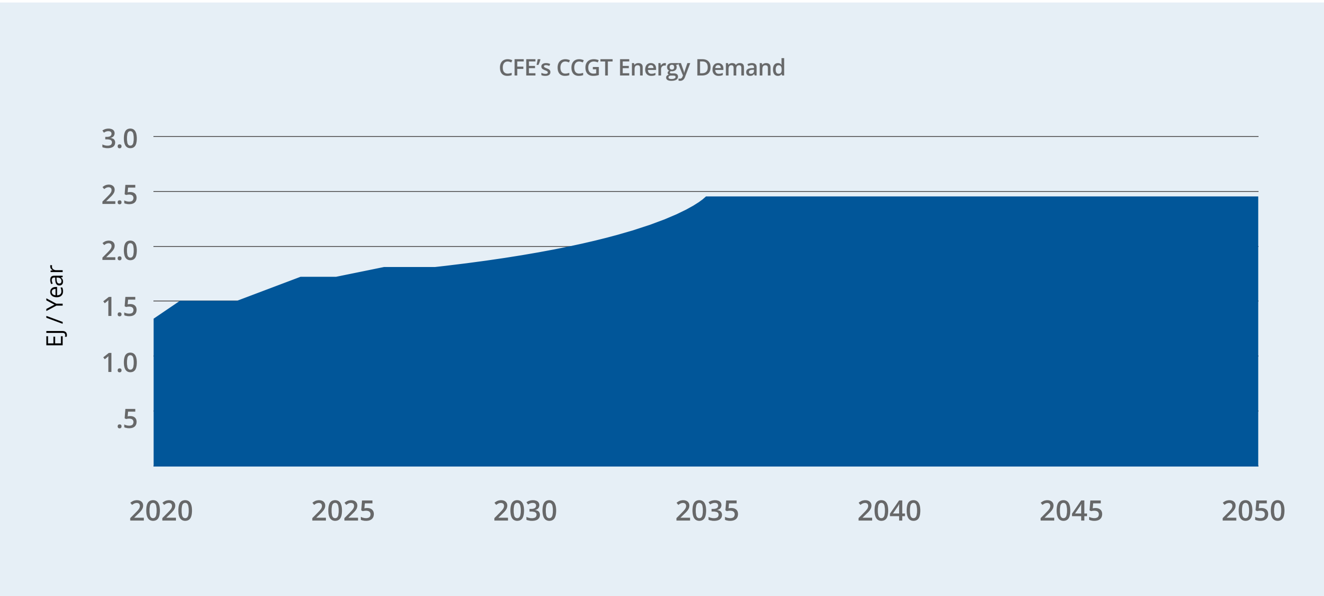
Figure 8-1. CFE installed capacity of thermal power in 2019.



There is neither current nor programmed hydrogen demand for power generation units. Hydrogen could make up for a minor but growing share of the fuel burnt in CCGTs, which can grow as technological developments allowing turbines to burn larger proportions of hydrogen or to run solely on it. In any case, the limit would be a proportion of the natural gas projected to be consumed. A reference for the amount of hydrogen which could eventually be demanded by CFE's thermal power generation is the total installed capacity of its CCGTs.

Simulations of the National Electric System were considered[14], which are based on SENER's National Electric System Development Program (PRODESEN), and the programmed capacity additions as reported by CFE. The results for projected installed capacity growth of CFE's CCGTs starts at 27,000 MW in 2020 and reaches 51,000 MW by 2034, where it is projected to halt, experiencing an increase of nearly 90% within that period. The corresponding energy demand which could partially be supplied in the form of hydrogen would be of 1.31 exajoules[15] (EJ) per year in 2020 to 2.48 in 2050, as shown in Figure 7-3. A minimal demand of hydrogen could also come from turbogas units but is negligible compared to CCGT demand and is disregarded in the results presented.

Figure 8-2. Projected energy demand in CFE's CCGT plants from 2020 to 2050.



8.2 Projected green hydrogen demand for thermal power plants

The projected cost evolution for both green hydrogen and natural gas is the same as considered in chapter 7, where they are compared on the basis of cost of the energy supplied by each, as shown in Figure 7-2.

In the NDC Compliance scenario hydrogen remains more costly and does not reach cost parity by 2050. By 2030 only companies producing hydrogen as a by-product would adopt hydrogen turbines, which is not the case for CFE. CFE would be testing the first small pilot projects with around 4 MW of combined electrolysis capacity installed and demanding less than 350 tons of hydrogen per year. A slow rate of adoption is projected until the last considered years, where the competitiveness gap is reduced to being only 30% more expensive than natural gas, allowing for a small boost in deployment by 2050 but reaching less than 500 MW of electrolysis for hydrogen re-electrification in specific regions with high renewable energy resources and difficult or costly access to natural gas.

In the Hydrogen Breakthrough scenario hydrogen remains at more than twice the cost of natural gas by 2030, but CFE would be deploying pilot projects with around 20 MW of electrolysis installed and demanding under 2 kilotons of hydrogen per year to test the combustion of a natural gas and hydrogen mix on its CCGTs. By 2042, green hydrogen will have reached cost parity with natural gas as a fuel for thermal power plants, boosting its deployment until 2050. By mid-century, up to 3.2 GW of electrolysis would have been installed to produce enough hydrogen to feed 3.5% of CFE's thermal power production capacity in CCGT units, with a demand of 270 kilotons of hydrogen per year.

[14] Simulations of the National Electric System from Deliverable 2 of this series are taken as input.
[15] 1 exajoule = 1018 joules

Figure 8-3. Projected hydrogen demand for thermal power plants in NDC Compliance and Hydrogen Breakthrough scenarios

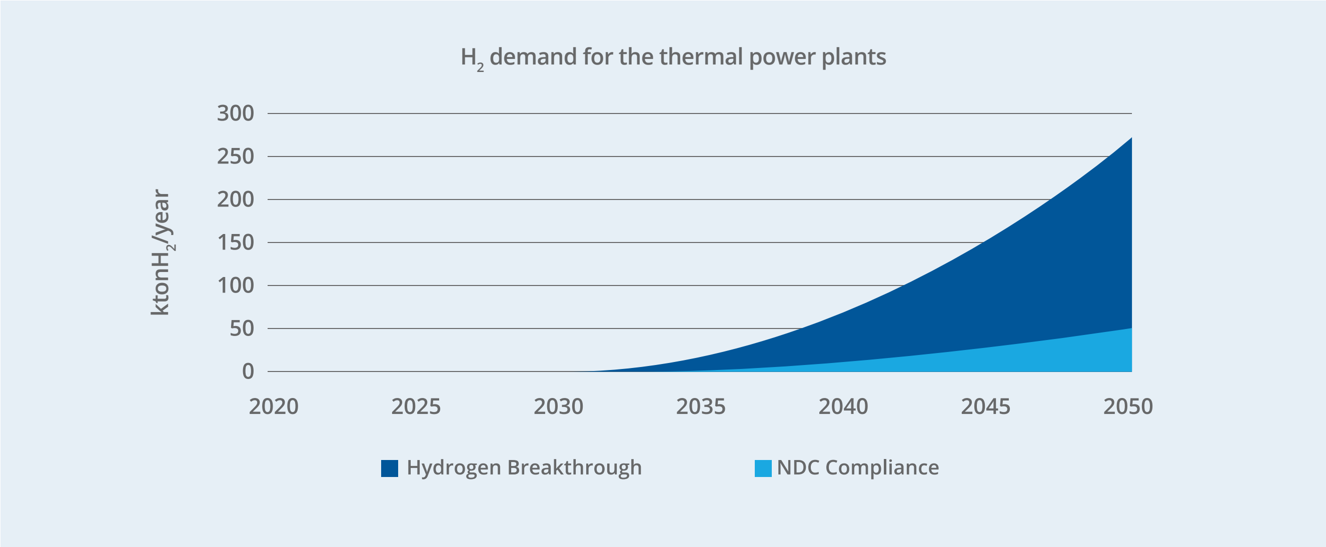
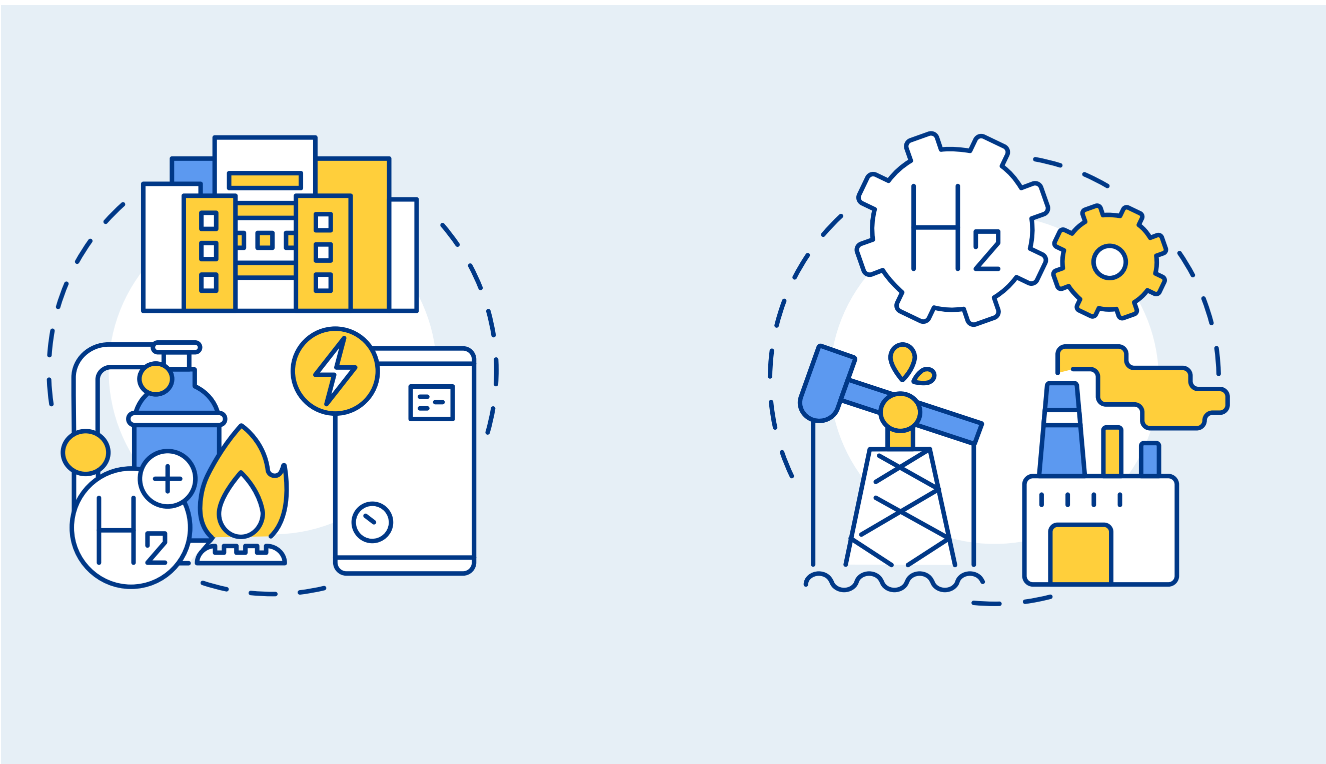


Table 8-1. Hydrogen demand and electrolyser capacity for power plants in 2030 and 2050.

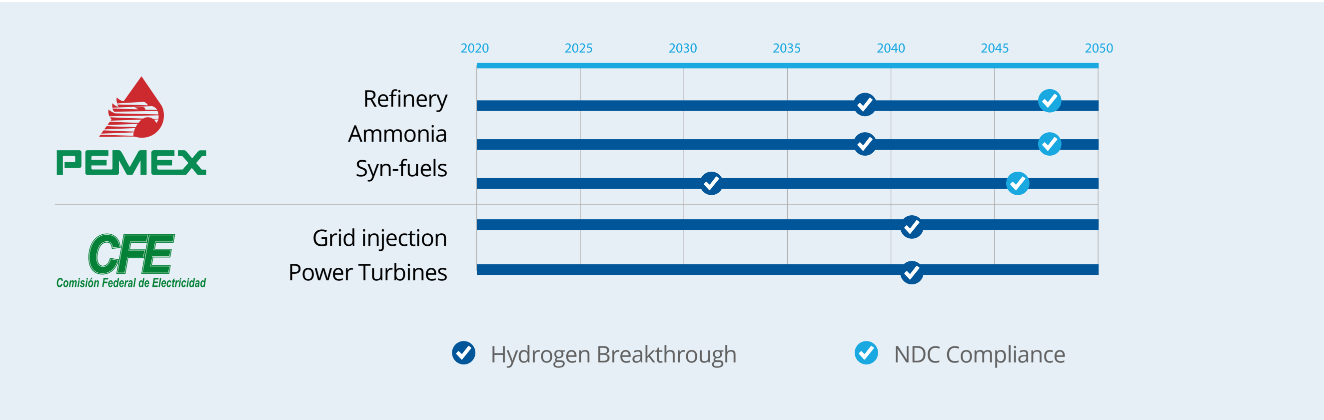
Thermal power plants	Hydrogen Demand		Electrolysis Capacity	
	2030	2050	2030	2050
NDC Compliance	<1 ktpa	50 ktpa	4 MW	630 MW
Hydrogen Breakthrough	2 ktpa	270 ktpa	20 MW	3,200+ MW



9. Conclusions

Cost-parity is the main driver for green hydrogen deployment across all applications. Considering all applications, synthetic fuels are the first end-use to reach cost-parity in 2032 (against diesel) in the Hydrogen Breakthrough scenario, and green hydrogen cost-parity is reached around 2040 for the remaining applications, where it competes with grey hydrogen. In the NDC Compliance scenario green hydrogen achieves cost-parity close 2050 or even after then for applications where it competes with natural gas, namely injection into the gas network and energy generation in thermal power plants.

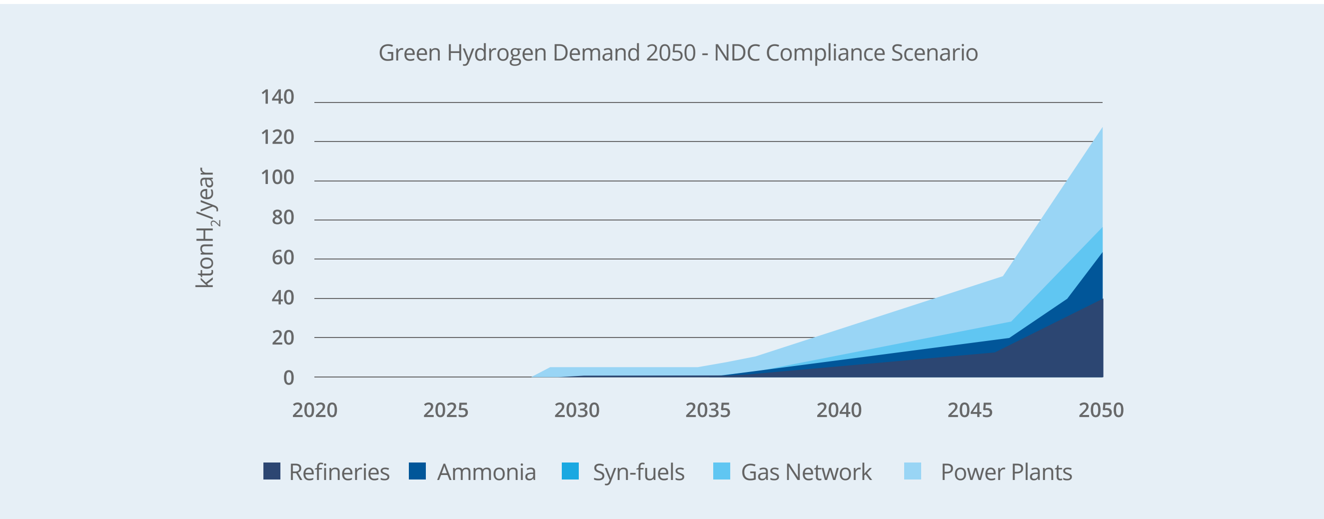
Figure 9-1. Projected times of cost-parity of green hydrogen for all end uses.



NDC Compliance Scenario

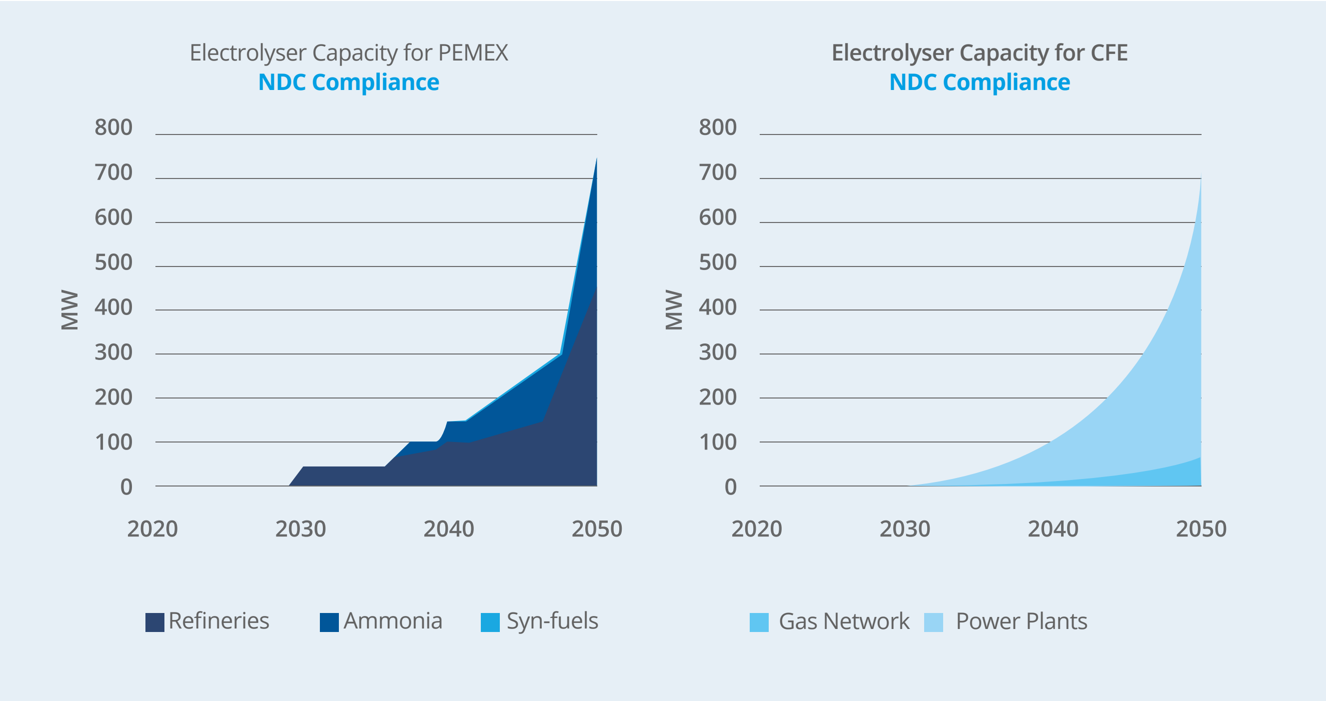
Green hydrogen is expected to struggle to reach economic competitiveness in Mexico for most applications, with minor adoption for all end uses in the NDC Compliance scenario, usually driven by climate mandates, and just starting to rise in the last years before 2050, when it is expected to reach cost parity for most applications. This results in a projected demand of under 60 kilotons of green hydrogen per year by 2047, expected to quickly rise to over 120 kilotons by 2050.

Figure 9-2. Projected hydrogen demand for all end uses in NDC Compliance scenario.



This implies only localized opportunities for both PEMEX and CFE before 2050, with larger potential for adoption in refineries and a growing share of ammonia for PEMEX and in thermal power plants for CFE for the second half of the century.

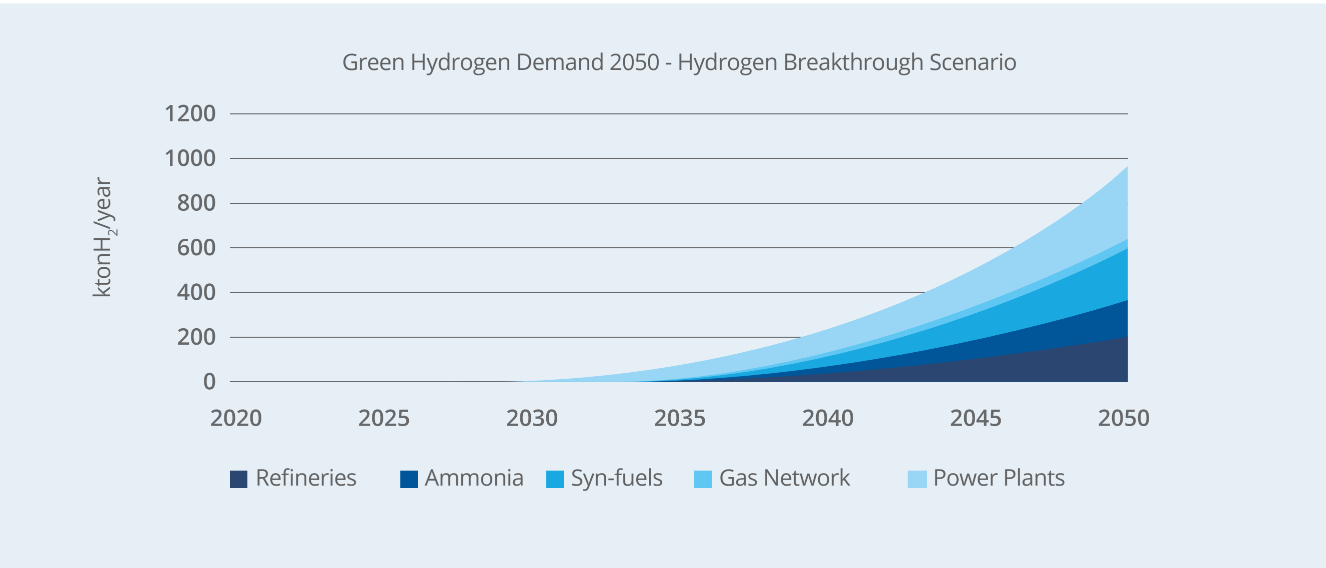
Figure 9-3. Electrolyser capacity required to supply the projected hydrogen demand for PEMEX and CFE in NDC Compliance scenario.



Hydrogen Breakthrough Scenario

In the Hydrogen Breakthrough scenario, a more uniform deployment across all segments is projected, with higher rates of growth in the decade of 2040 and reaching a demand of nearly one thousand kilotons of green hydrogen per year by 2050.

Figure 9-4. Projected hydrogen demand for all end uses in Hydrogen Breakthrough scenario.



Sizeable opportunities could be expected for PEMEX 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 (or half the national volume) 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 demand worth 800 million USD per year in 2050.

For CFE a relatively small demand is expected for injection in the gas network due to a low economic competitiveness even in this scenario and the largest opportunities are projected in hydrogen-powered 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 it will have a cost of 380 million USD every year by mid-century.

Figure 9-5. Electrolyser capacity required to supply the projected hydrogen demand for PEMEX in Hydrogen Breakthrough scenario.

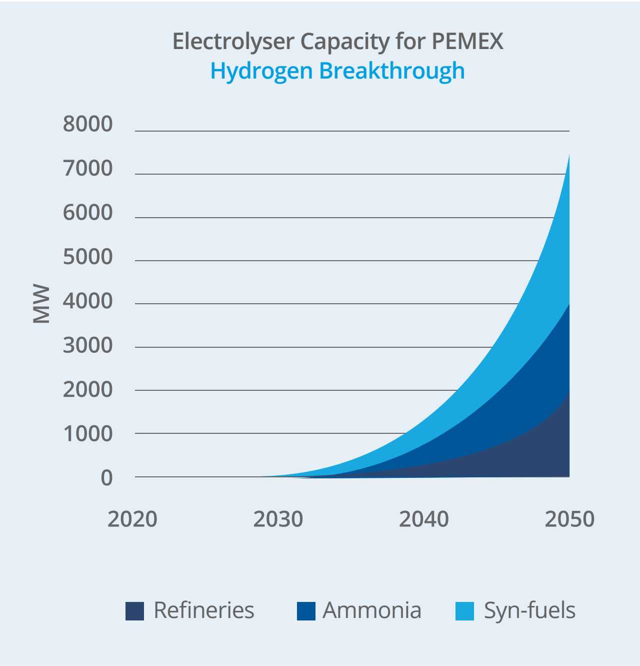
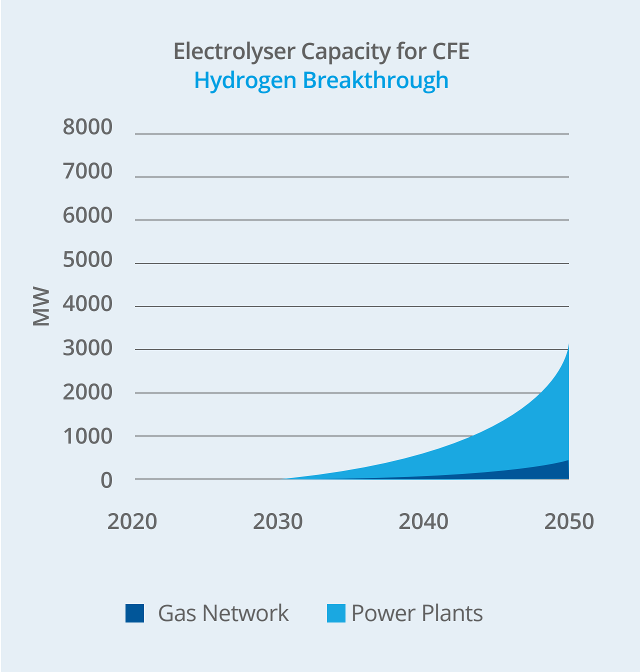


Figure 9-6. Electrolyser capacity required to supply the projected hydrogen demand for CFE in Hydrogen Breakthrough scenario.



Conclusions on opportunities for state-owned companies

State-owned PEMEX and CFE could lay the foundations for the development of a large-scale green hydrogen economy in Mexico. Following cost-competitiveness, the second largest challenge for the broad deployment of green hydrogen projects is to secure an off-taker for the hydrogen produced, usually with a green premium[16] on the cost, which both companies could have secured each for amounts larger than any project currently in development worldwide. 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[17] value chain to remain in the country along with the associated investments, jobs, and infrastructure.

PEMEX could take the lead in producing synthetic fuels for aviation as early as 2032, when they will be cost-competitive. However, even for this application, hydrogen adoption is projected to boom in the 2040's but could be accelerated drastically by adopting goals oriented with the sovereign energy transition and

16. The Green Premium is the additional cost of choosing a clean technology over one that emits a greater amount of greenhouse gases, according to Breakthrough Energy.

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

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.

Table 9-1. Projected electrolysis deployment and yearly hydrogen markets in 2050 for PEMEX (refineries, ammonia, syn-fuels) and CFE (gas network, power plants).

2050	PEMEX		CFE	
	Electrolysis	H_2 Market	Electrolysis	H_2 Market
NDC Compliance	770 MW	97 MMUSD/year	720 M	90 MMUSD/year
Hydrogen Breakthrough	7.5 GW	800 MMUSD/year	3.5 GW	380 MMUSD/year

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.

Table 9-2. Hydrogen demand and electrolyser capacity for all end uses in 2030 and 2050.

All end uses for PEMEX and CFE	Hydrogen Demand		Electrolysis Capacity	
	2030	2050	2030	2050
NDC Compliance	5 ktpa	130 ktpa	60 MW	1,500 MW
Hydrogen Breakthrough	30 ktpa	960 ktpa	400 MW	11,200 MW

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Appendix 1 – Assumptions and modeling inputs

General considerations

Some considerations apply for all sectors analyzed, which are described below:

Consideration	Description
Electricity costs	• As this study's objective considers green hydrogen analysis, the primary power sources considered were solar photovoltaic and wind power. • Levelized costs were calculated using CAPEX projections of 320 USD/kW for solar photovoltaics and 825 USD/kW for wind power by 2050.
Fossil fuel cost	• Fossil fuel's future costs were obtained from the Program for the National Electric System Development 2018 (PRODESEN). • PRODESEN 2018 includes three scenarios for fossil fuel costs evolution: (1): Low scenario, (2) Planned scenario, and (3) High Scenario. The study uses Planned Scenario for calculations related to the NDC compliance scenario and High Scenario to Hydrogen Breakthrough calculations.
Carbon pricing/tax	• Nowadays, Mexico has a tax (Special Tax for Production and Services, IEPS) for fossil fuels' carbon content (except natural gas). NDC Compliance scenario projects to 2050 the increasing trend that IEPS has had from 2014 to 2020. Natural gas is taxed by 2030 in this scenario. • In the Hydrogen breakthrough scenario, IEPS keeps growing as usual until 2030. From 2030 to 2050, it grows faster, reaching 60 USD/ton of CO_2 by 2050.
Sectors demand forecast	• The study uses official projections from SENER for the available sectors (Refining, Transportation fuels, and Thermal Plants capacity). (Crude Oil and Petroleum Prospective 2018-2032, Ministry of Energy, Mexico 2018) • For the sectors with no official forecast published, this study linked the international trends on the market with Mexico's characteristics like current market size, expected growth on the GDP, or market size of related goods, for example, fertilizers linked to ammonia. Specific considerations for each sector will be described on their "Considerations tables" below.

Consideration	Description

Levelized Cost of Electricity (LCOE)	• Just one forecast for electricity cost was calculated. Parameters considered for the calculations are "business as usual," and they are used for both green hydrogen penetration scenarios.
	• LCOE for solar PV was calculated using the following consideration:
	  · CAPEX 2050: 320 USD/kW
	  · OPEX: 2% of CAPEX per year
	  · Lifetime: 30 years
	  · LCOE for wind power calculated under the following assumptions:CAPEX 2050: 825 USD/kW
	  · OPEX: 3% of CAPEX per year
	  · Lifetime: 30 years
	• CAPEX and OPEX for renewable energy technologies were obtained from "Future of Wind" and "Future of Solar Photovoltaic" reports from IRENA (2019). For both technologies CAPEX are given as a wide possible range by 2050. This study takes conservative values close to the middle of the ranges, being them in the most probable area of a distribution curve.

Levelized Cost of Hydrogen (LCOH)	Two scenarios for Levelized Cost of Hydrogen were estimated:
	• The hydrogen Breakthrough scenario has a positive hydrogen cost evolution, following the best cost forecast for hydrogen infrastructure.
	  · CAPEX 2050: 300 USD/kW
	  · Electrolysis efficiency 2050: 48 kWh/kg H_2
	  · Stack Lifetime 2050: 90,000 hours
	• NDC Compliance scenario follows more conservative technical and economic projections under Business-as-Usual considerations.
	• CAPEX 2050: 450 USD/kW
	• Electrolysis efficiency 2050: 50 kWh/kg H_2
	• Stack Lifetime 2050: 80,000 hours
	• The electrolysis costs in 2050, the performance improvement and the stack lifetimes proposed by Hinicio are values within the projection ranges of conservative sources like IEA (The future of Hydrogen, 2019) and Bloomberg NEF (Green Hydrogen: Time to Scale Up, 2020)

Green hydrogen penetration	For both scenarios, green hydrogen penetration was calculated considering the following criteria: • Cost competitiveness: higher penetration is expected when hydrogen reaches the breakeven point with conventional technologies. • Technology adoption willingness: Hydrogen breakthrough scenario foresees an early green hydrogen adoption even before economic competitiveness due to pilot and demonstration projects. • NDCs by sector: sectors with the highest greenhouse gas mitigation goals adopt green hydrogen and other decarbonizing technologies faster. • Hydrogen technologies availability: global manufacturing capacity of some green hydrogen technologies is still limited, and it will grow in the coming years. The central technology taken into consideration for this study is electrolysis. • International context for green hydrogen adoption by sector and its comparison over alternative green or decarbonizing technologies, for example, batteries and pumped hydro versus hydrogen for energy storage.

Refineries

Consideration	Description
Common considerations	• According to the "Prospective of Crude Oil and Oil-bearing 2018-2032," the National Refining System will reach its maximum capacity by 2027, which will be constant until 2032. • Dos Bocas refinery is already considered on the National Refining System capacity forecast. • Hydrogen consumption of the National Refining System (either grey or green) was calculated with information reported in the Statistical Yearbook 2016 of PEMEX and hydrogen production reported by the same year in the White-book of Hydrogen Supply for the Tula Refinery (2018). • Each refinery of the National Refining System may have different volumes of hydrogen consumption depending on the characteristics of the crude being processed For this study, an average value of 0.75 kgH_2 / crude oil barel was used, obtained from the total volume of hydrogen consumed in 2016, divided by the volume of crude oil refined in that same year.. • From 2032 to 2050, no additional refineries were summed to the National Refining System.
NDC Compliance	• The Oil and Gas sector has a National Determined Contribution of 14%. However, green hydrogen is not expected to reach economic competitiveness by 2050. • By 2030, 1% of refineries' hydrogen would be covered by green hydrogen, with 48 MW of electrolysis. • Considering that the breakeven point of grey-green hydrogen is reached in 2047: the market share of green hydrogen in Mexico would be as low as 10%, representing 480 MW of electrolysis.
Hydrogen Breakthrough	• In this scenario, the willingness to adopt green hydrogen is more significant, and more ambitious pilot projects are expected. Up to 3% of grey hydrogen of refineries would be replaced by green hydrogen. • By 2030, up to 145 MW of electrolysis would be destined to produce green hydrogen for refineries. • The breakeven point between grey and green hydrogen is reached by 2038. • With 12 years of economic competitiveness, green hydrogen has developed a 2.4 GW of electrolysis capacity by 2050, replacing 50% of grey hydrogen from refineries in Mexico.

Ammonia

Consideration	Description
Common considerations	• It has been identified as a decreasing trend in ammonia production from 2010 to 2019, being zero in 2019. • Considering that PEMEX has a reported capacity of ammonia production of 4633 k ton NH_3/year and new contracts of natural gas supply are being signed by state-owned companies in Mexico, a recovery in the production of ammonia is expected. This study is assuming a symmetrical recovery of ammonia production from 2021 to 2030. • After 2030, continuous growth in ammonia production is forecasted to tie production with national demand. • According to international projections of fertilizer needs (IFA, Fertilizer Outlook 2019 – 2023, IFA Annual Conference, Montreal, Canada. 2019), the national ammonia demand was estimated with a growth rate of 1% annually in Mexico. • No technical improvements are expected in the Haber – Bosch process for ammonia production, maintaining the same hydrogen ratio of 0.176 ton H_2 per ton of ammonia.

Ammonia

Consideration	Description
NDC Compliance	• Green hydrogen is not yet economically competitive over grey hydrogen and NDC for the industrial sector is just 5% of GHG reduction concerning the baseline. • No green hydrogen penetration is foreseen by 2030 in this sector. • By 2050, green hydrogen has been fully competitive since 2047. It just has a 10% of market share in ammonia production, with 276 MW of electrolysis.
Hydrogen Breakthrough	• Even when the industrial sector has lower NDCs than the Oil and Gas sector, green hydrogen pilots and demonstration projects would be developed during this decade with up to 85 MW of electrolysis displayed by 2030, which is equivalent to 5% of the hydrogen demand of the sector in that year, a realistic value set on the context of European hydrogen roadmaps which expects, for example, 25% of industrial hydrogen to be green in Spain and up to 33% for the whole Europenan Union in the same year.Considering that 12 years of economic breakeven between grey and green hydrogen has elapsed by 2050, the installed capacity of electrolysis would represent 60% of hydrogen for ammonia production.

Synthetic fuels

Consideration	Descriptio

Common considerations	• The Levelized Cost of Synthetic Fuels was calculated with the study's proprietary tool, based on Enea 2016 and LBST/Hinicio 2019 information. LCOH is a variable of this methodology.
	• Different LCOH projections were used to estimate the cost of synthetic fuels for both scenarios.
	• For this analysis, synthetic fuels synthetic fuels were limited to synthetic liquid fuels with molecular weights between 155 (jet fuel) and 210 g / gmol (diesel)
	• Cost distribution of the Levelized Cost of Synthetic Fuels has the following evolution:
	  • CAPEX Power to Liquids: 33.2%(2020) – 43.5% (2050)
	  • OPEX Power to Liquids: 6.7% (2020) – 8.8% (2050)
	  • CO_2: 12.3% (2020) – 9.5& (2050)
	  • Hydrogen: 47.3% (2020) – 37.8% (2050)
	  • Electricity (PtL process): 0.5% (2020) – 0.4% (2050)
	• Synthetic fuel costs are compared with fossil fuel costs to find out the breakeven point between them. Green hydrogen is a significant component of syn-fuels cost.
	• This study is focused on fuels for aviation transport. Alternative fuels like ammonia could energize maritime transport and pure hydrogen could power trains.

NDC Compliance	• The transport sector has an 18% of GHG reduction, according to the Mexican NDCs. However, aviation consumes just 7.8% of the sector's energy, while terrestrial transport consumes 89.8%. • Considering the low contribution of aviation to Mexican emissions and the no economic competitiveness before 2046: no penetration of syn-fuels is expected by 2030. • By 2050, synfuels have been competitive for 5 years, then, just 3,000 tons/year of synthetic fuel production capacity have been developed.

Synthetic fuels

Consideration	Description
Hydrogen Breakthrough	• In this scenario, the favorable cost forecast for syn-fuels and the aggressive cost increasing projected by SENER for liquid fossil fuels (+6.6% annually): breakeven point occurs in 2032. • Even when Power To Liquids is not yet a mature technology, some medium-scaled projects are developed before 2030 (40 kton Syn-fuel/year) • By 2050, the technological maturity and economic competitiveness would drive to 1200 kton syn-fuel/year of installed capacity.

Injection in gas networks

Consideration	Description
Common considerations	• According to SENER projection of natural gas demand and this study's extrapolations of the trends (last 10 years) of increase in the demand for this substance, the market would grow from 8,325 MMSCFD in 2020 to 12,190 MMSCFD in 2050. • Sectors of interest in these hydrogen applications are those who consume natural gas with thermal proposes. • As green hydrogen is used for thermal applications, cost competitiveness is evaluated by comparing fuel costs in USD/MMBTU.
NDC Compliance	• Green hydrogen doesn't reach economic competitiveness by 2050 for this scenario. • Just small demonstration projects or by-product green hydrogen is expected to be injected into gas grids by 2050. • By 2050, green hydrogen cost will be very close to natural gas cost. More significant sized projects are expected in a decarbonizing economy, which could consume up to 8 to 10 kton H_2/year.
Hydrogen Breakthrough	• Breakeven point between green hydrogen and natural gas is expected by 2042. • By 2030, between 30-35 MW of electrolysis for mixed hydrogen-natural gas pipelines would be displayed, according with the technological trends. • Even when green hydrogen will be economic competitive over natural gas by 2042, some consumption technologies (burners, boilers, turbines etc) will be ready to consume pure hydrogen between 2030 and 2040. • Internationally, just 5% of green hydrogen is expected to be used in residential applications by 2050. From these 5%, 95% will be transported by dedicated pipelines and 5% in a mix with natural gas. • Considering it, no more than 40 kton H_2/year will be injected into gas pipelines by 2050.

Thermal power plants

Consideration	Description
Common considerations	• The installed capacity by year for each thermal plant technology was obtained from PRODESEN 2019 (from 2020 to 2033) and extrapolated to 2050 according to the trends observed in the previous 10 years (2009-2019) in the technological switch for thermal power plants in Mexico. • Due to their potential to consume green hydrogen and the forecasted growth in deployment: combined cycles and turbo gas units are of interest for green hydrogen adoption. • Simulations of the National Electric System from Deliverable 2 of this consultancy are taken into consideration.

Consideration	Description
NDC Compliance	• Natural gas keeps cheaper than hydrogen for the period studied. By 2050 green hydrogen will be still 30% more expensive (in USD/MMBTU). • By 2030 just companies with hydrogen as a by-product would adopt hydrogen turbines, due to the lack of economic competitiveness of green hydrogen. • By 2050 less than 500 MW of electrolysis capacity has been installed to hydrogen re-electrification in a specific region with difficult access to natural gas pipelines.
Hydrogen Breakthrough	• By 2030 just pilot projects of low capacity are being developed for green hydrogen in thermal power plants. • By 2042, green hydrogen is as cheap as natural gas as a fuel for thermal plants. • By 2050, up to 3.2 GW of electrolysis would have been installed to produce enough hydrogen to feed 3.5% of the national production capacity via combined cycles and 26% of the projected capacity production via turbo gas units.