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Green Hydrogen in Mexico: towards a decarbonization of the economy

Volume IV: Opportunities for the private sector

giz Deutsche Gesellschaft
für Internationale
Zusammenarbeit (GIZ) GmbH

Imprint

Commissioned and published by
Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH Registered offices Bonn and Eschborn

Programs

Bilateral Energy Partnerships in Developing and Emerging Countries & Energy Transition Support Program in Mexico (TrEM)

www.energypartnership.mx
www.giz.de/en/worldwide/76471.html

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As at
October 2021

Digital Version

Design

Sk3 Estudio Creativo, CDMX
www.sk3.mx

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página 7, 9, 13, 15, 22, 25, 29 y 31.

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Acknowledgments

Special acknowledgments

Patrick Maio (HINICIO)
Ana Ángel (HINICIO)
Luis Miguel Diazgranados (HINICIO)
Jorge Luis Hinojosa (HINICIO)
Juan Antonio Gutiérrez (HINICIO)

Content

Abbreviations

ANIQ	National Chemical Association, Mexico
CAEX	Camiones de Extracción, Mining haul trucks
CAMIMEX	Mining Chamber of Mexico
CANACERO	National Chamber of the Iron and Steel Industry
CAPEX	Capital Expenditures
CCGT	Combined Cycle Gas Turbine
CCUS	Carbon Capture, Use, and Storage
CFE	Comisión Federal de Electricidad, Federal Electricity of Commission
CONAGUA	Comisión Nacional del Agua, National Water Commission
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FCHEA	Fuel Cell and Hydrogen Energy Association, USA
GHG	Greenhouse Gas Emissions
H2B	Hydrogen Breakthrough Scenario
INEGI	National Institute of Statistics and Geography
LCOH	Levelized Cost of Hydrogen
LULUCF	Land Use, Land-Use Change, and Forestry
MW	Megawatt
NDC	NDC Compliance Scenario
NDCs	Nationally Determined Contributions
PEMEX	Petróleos Mexicanos, Mexico's National Oil Company
PRODESEN	National Electric System Development Program
SDGs	Sustainable Development Goals of the United Nations
SE	Secretaría de Economía, Ministry of Economy
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 (H2 production)
UNFCCC	The United Nations Framework Convention on Climate Change

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Executive Summary

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.

In the mining and metals industry hydrogen can be used to fuel hydrogen-powered fuel cell electric vehicles, mainly haul trucks; to reduce mineral ores, mostly iron to produce steel, and in thermal applications where hydrogen can be directly combusted to generate heat. In the cement industry, the largest potential for hydrogen is foreseen in supplying high temperature heat in the production process, which is the sector's largest source of GHG emissions. The chemical industry could also make use of green hydrogen for thermal energy generation, where its largest potential lies, or it can be used as a chemical feedstock to replace the existing gray hydrogen supply for the production of flat glass, synthetic resins, or margarines, all addressed in this study.

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' (H2B), which makes more optimistic assumptions following the projections of the Hydrogen Council.

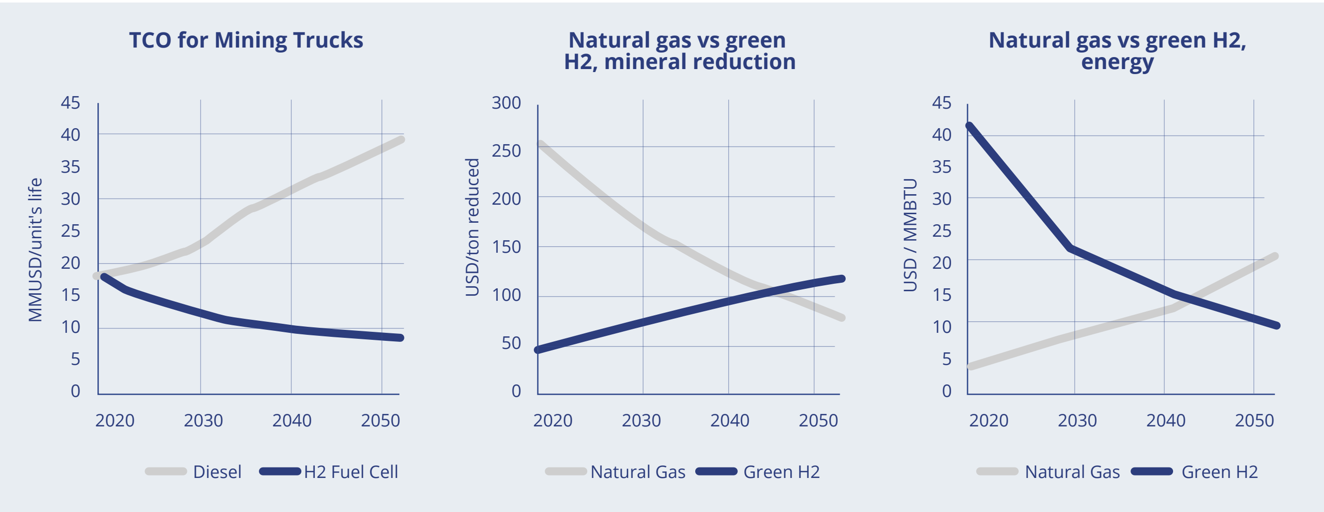
In 2050 the cumulative demand of green hydrogen for all the industries studied will reach 580,000 tons per year, requiring 6,750 MW of electrolysis capacity, and have a value of over 700 million dollars per year.

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 H2B, following a sharp decline in hydrogen technology costs in the preceding decade. LCOH in 2050 for NDC is still over 20% higher than H2B with 1.50 and 1.22 USD/kg, respectively.

Green hydrogen in mining and metals

Hydrogen demand will remain low until 2040. In 2042 demand will rise in the H2B scenario as it reaches cost parity along with electrolysis capacity installed, however it will remain stagnant in the NDC scenario where it will not achieve economic competitiveness by 2050. For both scenarios, thermal applications will represent a small share of the hydrogen demand, while hydrogen-powered mobility in mines and mineral reduction will each consume large and similar shares of hydrogen by 2050.

Figure A. TCO curves of diesel and H2 FCEV mining trucks (left), natural gas vs green hydrogen for mineral reduction (center), and for energy (right) in H2B Scenario.



Green hydrogen in cement

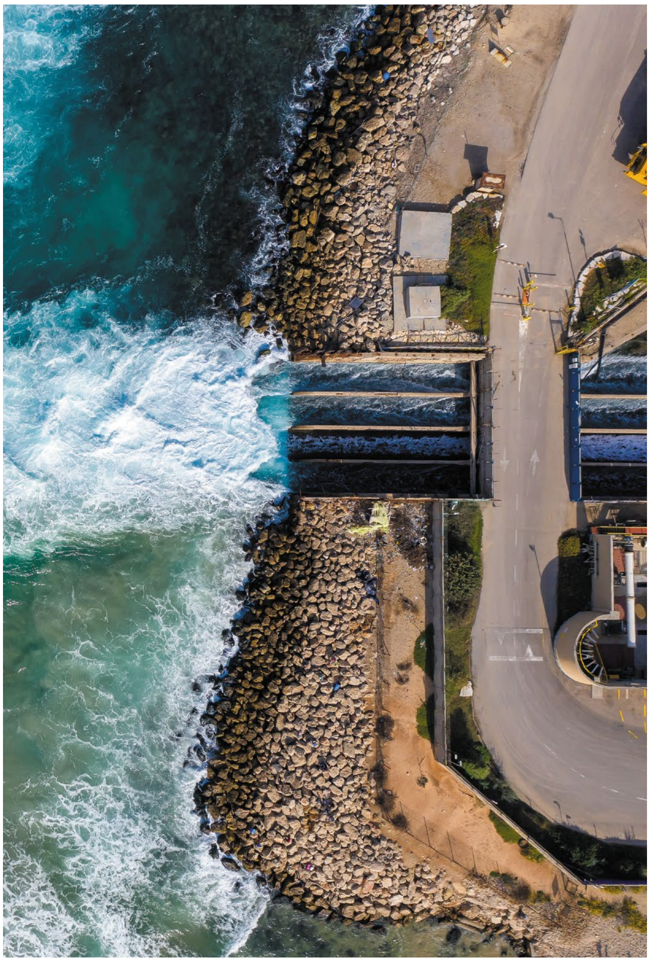
In 2050 green hydrogen will be closer to be cost-competitive with natural gas in the NDC scenario, with only 2% being replaced with green H2. In the H2B scenario, early pilot projects will start to be implemented in 2026 and by 2050, an average of up to 10% of the energy delivered by natural gas for cement in the country could be delivered instead by green hydrogen, or around 3% of the sector's total. This would amount to a demand of 36,000 tons of hydrogen supplying 4.3 PJ of energy per year, requiring and installed capacity of nearly 420 MW dedicated to the cement industry.

Green hydrogen in the chemical industry

The possibility of introducing and increasing a share of hydrogen content in a blend with natural gas could contribute gradually to supply more than 100 PJ per year of the energy demanded by the sector in mid-century. By 2050 the deployment of electrolysis for thermal applications could be up to 500 MW, which would represent a replacement of 5% of natural gas in the sector and demand 45,000 tons of hydrogen per year. As a chemical feedstock the resulting projected green H2 demand is very low compared to other segments, since only a few kilograms of hydrogen are required for each ton of the materials produced and it competes in cost directly with gray H_2.

Green hydrogen and water desalination

Splitting the water molecule into hydrogen and oxygen in an electrolyzer today requires approximately 16 liters/kgH_2 and may reach 11 liters/kgH2 as efficiencies improve. The demand for green hydrogen in Mexico in the H2B scenario of around 18 GW of electrolysis by 2050 would consume up to 17.3 hm3 of water, representing just 0.006% of the current consumption in Mexico. In regions where the resource is scarce and sea water is available, such as the Baja California Sur peninsula, water desalination will be required for hydrogen production. A case study reveals that the additional investment would imply an increase of less than 1% of the CAPEX per MW required for electrolysis.



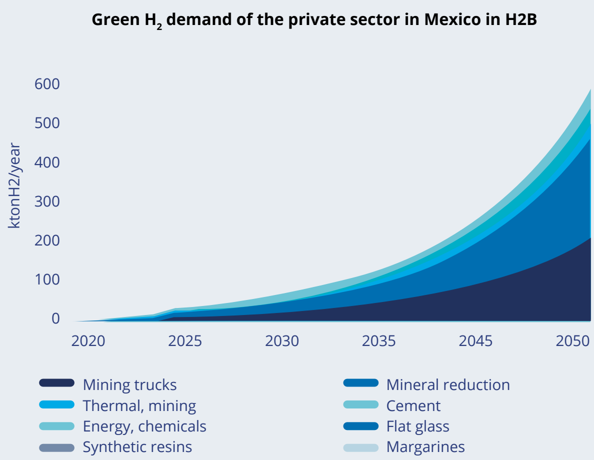
Private sector conclusions

In the **NDC Compliance** scenario, the mining sector presents the largest opportunities for green hydrogen, especially in mining trucks where hydrogen FC CAEX are already close to cost competitiveness, as well as for mineral reduction applications. The area of opportunity that follows in size is found in supplying energy to the chemical industry from green H_2, mainly substituting natural gas. Hydrogen uses for thermal applications in the mining and cement industries will be of a smaller scale. In 2050 the cumulative green hydrogen demand for all applications for the private sector will be of 280 kilotons per year and require an electrolyser capacity of 3,250 MW by 2050. At this moment, the green hydrogen market in Mexico will have a value of 420 million dollars annually.

In the **Hydrogen Breakthrough** scenario, prevalence remains for mobility applications in mining and mineral reduction, which together account for nearly 80% of the projected demand by 2050. By mid-century green H_2 demand reaches 250 kton/year for mineral reduction, 210 kton/year for mobility in mining, and more moderate demands for thermal applications in the chemical and mining industries and in cement, all in the range of 35- 45 kton/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 per year.

Opportunities as a chemical feedstock for flat glass, synthetic resins, and margarines will be negligible in comparison to the national green hydrogen market for both scenarios.

Figure B. Projected hydrogen demand for all end uses. Opportunities for the private sector in Mexico for the Hydrogen Breakthrough scenario.



1. Introduction

Green hydrogen can provide opportunities for companies in the private sector to adopt across their value chains, with major applications in energy, mobility, and as a feedstock for different industries. Companies worldwide see green hydrogen as a key vector for the decarbonization of a wide array of processes to comply with climate goals and the advent of the hydrogen economy is expected to set the ground new business opportunities and value creation globally[1].

Mexico already consumes close to 20 million dollars' worth of hydrogen aside from PEMEX every year according to the National Chemical Industry Association[2] and has the renewable energy resources and a strong industrial environment to develop a green hydrogen sector.

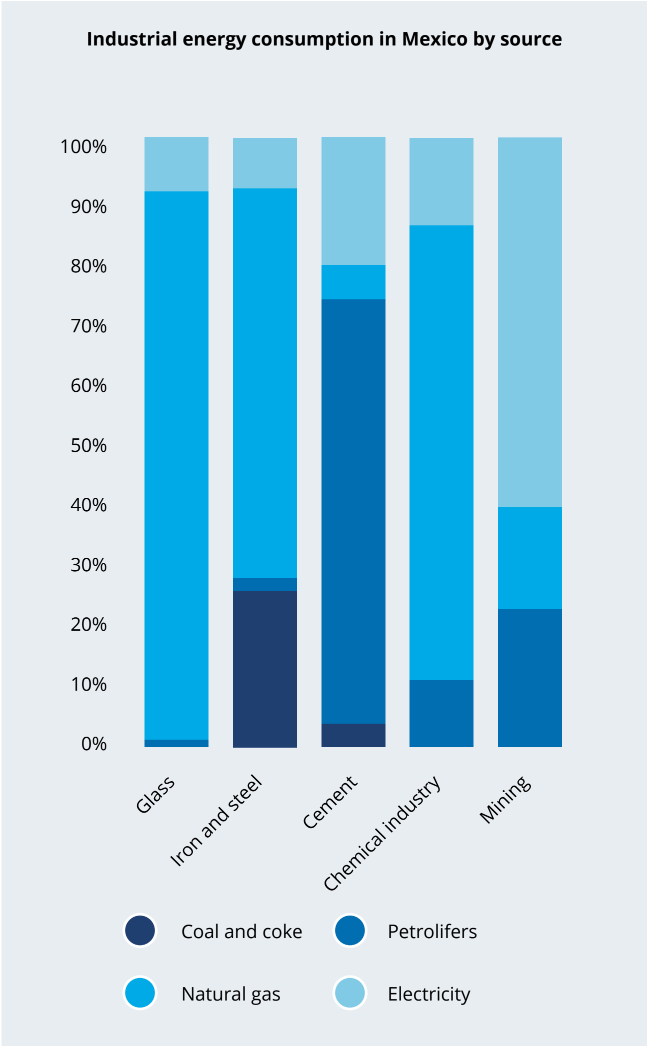
This study presents potential business opportunities in green hydrogen for the private sector in Mexico and presents the projected demand and cost curves for three key areas of application: the mining and metals industry, the cement industry, and the chemical industry.

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 gray hydrogen, which is produced mainly from steam reforming processes (SMR) of natural gas or coal, 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.

In the mining and metals industry hydrogen can be used to fuel hydrogen-powered fuel cell electric vehicles, mainly haul trucks; to reduce mineral ores, mainly iron to produce steel, and in thermal applications in which the hydrogen can be directly combusted to generate heat. In the cement industry, the largest potential for hydrogen is foreseen in supplying high temperature heat in the production process, which is the sector's largest source of CO2 emissions. The chemical industry could also make use of green hydrogen for thermal energy generation, where the largest potential lies and as a chemical feedstock to replace the existing gray hydrogen supply.

For thermal applications, hydrogen can be initially mixed with natural gas to combust as a blend. As the price of green hydrogen decreases and the technology matures, the share of hydrogen in the gas blend could be increased to eventually achieve a full replacement. This could provide an opportunity to reduce carbon emissions in the industries included in this report, which rely mostly on fossil fuels as their energy source and where natural gas plays a major role, as shown in Figure 1.1.

Figure 1.1. Structure of industrial energy consumption in Mexico by type of energy for selected industries, 2017. Source: Hinicio with data from SENER.



[1] Hydrogen Council, Hydrogen Scaling Up, 2017.
[2] ANIQ, Anuario Estadístico de la Industria Química 2019.


Visitors activity statistics
activity by day
Visits
Mar 15
Mar 22
Mar 29
Apr 5
Visits
375
Unique Visitors
286
Pageviews
947
Pages / Visit
2.53
Avg. Visit Duration
00:02:07
Bounce Rate
46.13%
% New Visits
68.27%
New Visitor
Returning Visitor
31.7%
68.3%

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 the private sector in Mexico up to 2050. Figures of merit were defined using industry interviews and reports, bibliographic reviews from publicly available documents and websites, and the authors' technical and commercial expertise in green hydrogen as inputs.

Two realistic scenarios are presented: 'NDC Compliance', which assumes Mexico will fulfill its climate commitments to comply with the Paris Agreement according to the Nationally Determined Contributions (NDCs); and 'Hydrogen Breakthrough', which makes more optimistic assumptions with high industry adoption and intensive policy support worldwide and in Mexico, following the projections of the Hydrogen Council.

Cost estimations and comparisons of the conventional alternative with the hydrogen one were made for each segment. The required levelized cost of hydrogen (LCOH) was calculated using 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 gray hydrogen alternative, i.e., the projected LCOH vs the target LCOH.

Figure 2.1. Methodologic process of green hydrogen demand projections

01	HYDROGEN SCENARIOS	Two realistic scenarios are presented with assumptions for H2 cost trajectories, across five themes, and those specific to each end-use.
02	DEFINITION OF FIGURES OF MERIT	Using industry interviews, bibliographic reviews, and the authors´expertise in H2. These are inputs for the projections and analyses.
03	GREEN H_2 LCOH PROJECTION	Cost projections for green hydrogen production are made using Hinicio models for LCOH in Latin America countries and adapted to the Mexican context.
04	CONVENTIONAL H2 COST & DEMAND PROJECTIONS	Projections are made to estimate the national addressable demand and the cost of gray hydrogen or the conventional solution for all applications, resultina in a target LCOH for
05	GREEN H_2 DEMAND PROJECTIONS	Economic competitiveness is compared against the conventional technology to find the time of cost parity and projections of the green H2 demand and electrolvsis capacity are made for each end use.

The inputs for these projections of cost evolution of hydrogen include the current and historical prices of the conventional alternatives, such 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 (NDC) scenario is based on the assumption that Mexico will fulfill its climate commitments to comply with the Paris Agreement according to the NDCs it submitted in 2015. This scenario considers that the country implements 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 on December 2019[3]. 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.

[3]SEMARNAT: Process for updating Nationally Determined Contributions (NDC), 2020.

Table 2.1. Mexico's NDC commitments for GHG reductions by segment to 2030. Source: Government of Mexico[4].

	Projected BAU (MtCO2e)	Projected NDC (MtCO2e)	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[6]	32	-14[7]	144%
Total	**972**	**762**	**22%**

The **Hydrogen Breakthrough (H2B)** 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[5]. 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 hydrogen scenarios in Decarbonization Goals. Source: Hinicio

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 hydrogen technologies	Mexico complies with its climate commitments for 2030. Hydrogen has a market share according to its cost-competitiveness for each segment	Mexico keeps fulfilling its climate commitments according to its NDCs. 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 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. 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 hydrogen value chain.

Table 2.3. Assumptions for hydrogen scenarios in Sovereign Enrgy Transitions. Source: Hinicio

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 hydrogen in its regulatory framework as a decarbonization and energy vector	The Mexican energy transition includes nationally produced hydrogen, with growing but conservative market shares	Mexico has significant advancements towards a highly renewable energy matrix with hydrogen playing a key role in sector integration and decarbonization. Mexico comes closer to being energy self-sufficient

[4] Intended Nationally Determined Contribution of Mexico, 2015.
[5] 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 2.4. Assumptions for hydrogen scenarios in Public and Private Investment. Source: Hinicio.

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 hydrogen are made in segments where it has become cost-competitive	Mexico's investments in hydrogen have increased since 2030, as it reaches cost parity in new segments
Hydrogen Breakthrough	Public and private actors begin to plan investments in hydrogen technologies that allow tests before they are fully competitive in the market	The hydrogen ecosystem in Mexico is maturing, with pilot projects in most segments. There is an early adoption of hydrogen technologies as they reach cost parity	Investments in hydrogen have continued to rise from 2020 to 2050. Mexico has a mature 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 hydrogen scenarios in Cost Competitiveness. Source: Hinicio.

Competitividad de costos	2020	2030	2050
NDC Compliance	Hydrogen is 100% competitive with other technologies in very few applications	Hydrogen has had a "Business as Usual" improvement in costs. Hydrogen is 100% competitive for some niche applications	Green H2 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	Hydrogen is 100% competitive compared with other technologies in very few applications	The global push for 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 hydrogen demand are met

Table 2.6. Assumptions for hydrogen scenarios in Technical Development. Source: Hinicio.

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	Hydrogen has modestly improved its performance under a BAU scenario	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 H2 applications equal to or better than 2020 projections. Consequently, hydrogen acquires market shares equal to or greater than those foreseen by the Hydrogen Council in 2020

A more detailed account of this assumptions as well as those for each specific segment and scenario can be found in the Appendix.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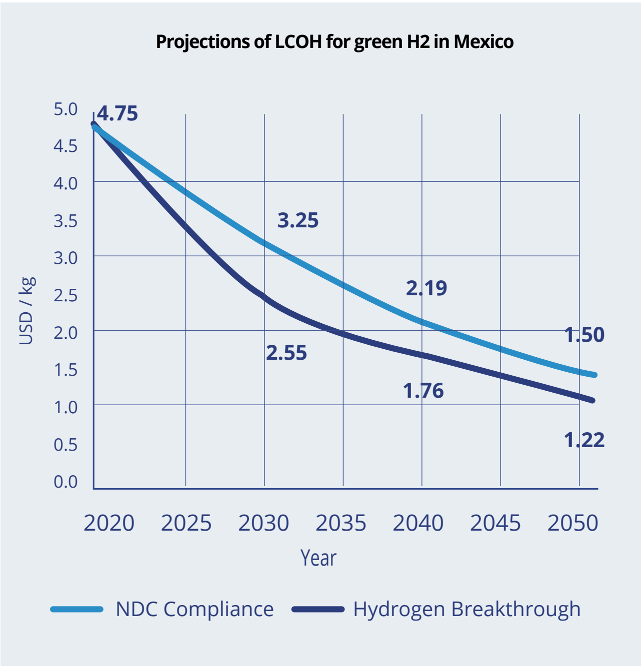
3. Projections of LCOH for green hydrogen

Cost projections for green hydrogen were made using 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 the pace of the evolution 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 widest LCOH gap is in 2030 with 3.25 USD/kg in NDC Compliance and 2.55 USD/kg in Hydrogen Breakthrough, given the highly accelerated decrease in the cost of the technology in the previous decade in the latter scenario. LCOH in 2050 for NDC Compliance is still over 20% higher than Hydrogen Breakthrough with 1.50 and 1.22 USD/kg, respectively, with the cost of electrolysers continuing to drop in both scenarios but without filling the cost gap between scenarios before mid-century.

The resulting cost curve for green hydrogen or LCOH evolution from 2020 to 2050 shown in Figure 3.1 was later used for comparison with the projected curve of the target LCOH for each application to find the point of cost parity for both scenarios.

4. Opportunities in green hydrogen for the mining and metal industry

Mining companies worldwide are striving to achieve their climate goals and contribute to the transition to carbon neutral systems, being currently responsible for 4% to 7% of GHG emissions at a global level. Having a cleaner mining industry could yield minerals with lower carbon content and contribute to decarbonize value chains across a wide range of industries. However, decarbonization remains a challenge for the mining sector. Companies are looking for viable technologies to address this challenge without reducing their processes' efficiencies, providing an opportunity for dynamic, renewable energy-based solutions such as those provided by green hydrogen.

Possibilities for hydrogen can be found in mining processing applications such as mineral reduction, powering mining trucks, and electricity generation with flexibility to address the challenging operational conditions of mining sites. Locally produced and emissions-free green hydrogen could replace diesel to power vehicles and backup generators in mines, which would otherwise need to be transported to remote sites, carrying with them associated costs and carbon emissions. Additionally, the use of hydrogen and fuel cells instead of fossil-fuels could help protect the health and safety of mine workers.

The metal processing industry is also facing pressure to reduce its environmental impact, particularly steel which is among the three largest emitters of carbon dioxide with around 8% of global carbon emissions[6], and contributing to the infrastructure of a low-carbon economy. Opportunities for green hydrogen in the steel industry lie on the iron ore reduction process, which can take different technological routes and where it could replace either coal coke or natural gas, and by supplying high temperature heat to its furnaces, which are currently fueled mostly by coal.

The hydrogen applications considered in this report for mining and metals industry are divided in three end-use categories:

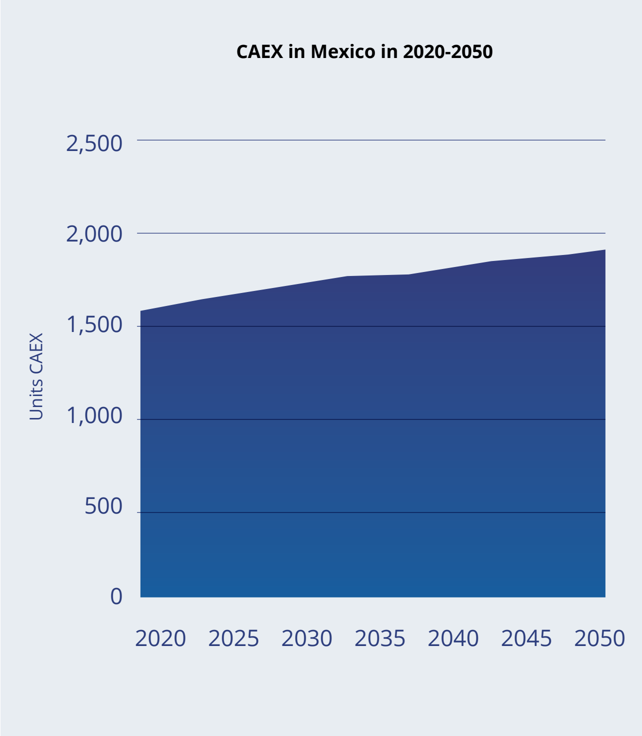
1.	Haul trucks
2.	Mineral reduction
3.	Thermal applications

4.1. Haul trucks

4.1.1. Hydrogen demand for haul trucks

There is no current demand of hydrogen for mobility applications in the mining sector in Mexico, which is fueled with fossil sources. To account for the fuel demand to be potentially replaced by hydrogen, the number of CAEX[7] vehicles in operation and mineral extraction volumes are considered. Historical import information of mining trucks is taken from the Ministry of Economy´s trade balance of Mexico[8], focusing on high tonnage dumper trucks. It is to be noted that in the 2003-2020 period over 60% of the CAEX imported came from the United States, followed by the UK and Japan with considerably smaller shares.

Figure 4.1. Projected number of CAEX units in Mexico in 2020-2050. Source: Hinicio projection, based on data from the Ministry of Economy and CAMIMEX.



After 2020, the CAEX units and fuel demand to be potentially substituted by hydrogen is considered to be proportional to the projected extraction of minerals in the country, using copper as reference with estimations taken from the Mining Chamber of Mexico.

[6]McKinsey & Company, Decarbonization challenge for steel, 2020.
[7]CAEX: mining haul trucks (from "Camiones de Extracción" in Spanish)
[8]Ministry of Economy, based on the Tax Administration Service (SAT), Bank of Mexico, INEGI. Trade Balance of Merchandise of Mexico 2003 - 2020.

4.1.2. Projected green hydrogen demand for haul trucks

An existing demand of hydrogen for mobility in mines is dependent on the deployment and operation of hydrogen-powered vehicles on site. Although already cost-competitive in 2021, technological adoption will remain slow in the early 2020's due to the lack of commercial availability of FC CAEX units as well as the infrastructure required to run them. The technology is still in a development stage, with technological challenges to solve and promising advances involving some of the largest players in the industry worldwide, including mining major Anglo American and leading haul truck manufacturer Komatsu[9]. The first commercial units to come online globally could be deployed around 2024, regardless of the scenario considered.

For cost-comparison, the Total Cost of Ownership (TCO) was calculated for both conventional diesel and for hydrogen fuel cell powered CAEX. The TCO integrates the costs of acquisition, installation, operation, maintenance, and all costs for the owner throughout the vehicle's lifetime, as well as their associated infrastructure's which includes hydrogen storage and refueling stations in the case of FC CAEX. Thus, a number of variables were projected in the studied period to obtain a consolidated measure of economic comparison between fossil and hydrogen fueled vehicles, normalized to a TCO in dollars per unit considering equal lifetimes of 10 years and operation rates for a direct assessment. Such variables include the CAPEX for the vehicles, including their fuel cell technology and electric batteries, green hydrogen production and handling infrastructure, considering an evolving LCOH, CO2 taxes, diesel costs, and other factors.

NDC Compliance

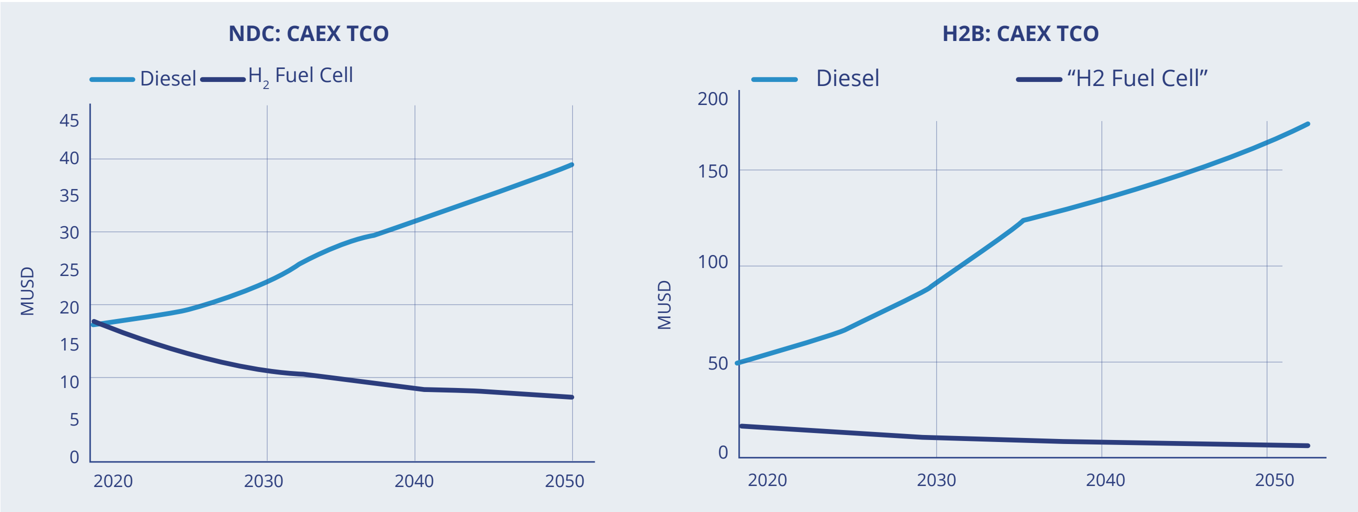
Cost-competitiveness of hydrogen and fuel cells in CAEX is already achieved in 2021, but the first pilots can be expected until the next decade following the lack of supply of the vehicles, the novelty of the technology, considerable investments required to scale, and non-compelling government or environmental incentives. By 2030, mining CAEX will be considerably more economically competitive than diesel ones. However, production numbers will still be small compared to conventional CAEX, with not much recharging infrastructure having been deployed. In Mexico, there could be a pilot project with a few units running, and mining CAEX will not contribute to compliance with the mining sector NDCs. Up to this point hydrogen demand would be negligible but expected to grow in the following decades.

By 2050 the FC CAEX will already have charging infrastructure deployed and will be the commercially competitive mining option, being around four times cheaper than diesel alternative. The expected penetration of CAEX FC for this year corresponds to 41% of the national fleet, with over 800 fuel cell vehicles deployed and a green hydrogen demand of over 100 thousand tons per year being a contributor to the sector´s NDC in Mexico and requiring an electrolyser capacity above 1,300 MW.

Hydrogen Breakthrough

n 2021 fuel cell CAEX will be significantly more competitive than diesel ones, at around one quarter of the TCO. The lack of FC CAEX supply and hydrogen infrastructure deployment in mines will allow the first units to start coming online until 2027 through pilot projects and take-off in 2030 once broader global supply is established. In this decade, deployment will grow considerably surpassing 300 units in 2040 and further accelerating to grow five-fold and reach 1,500 FC CAEX in 2050.

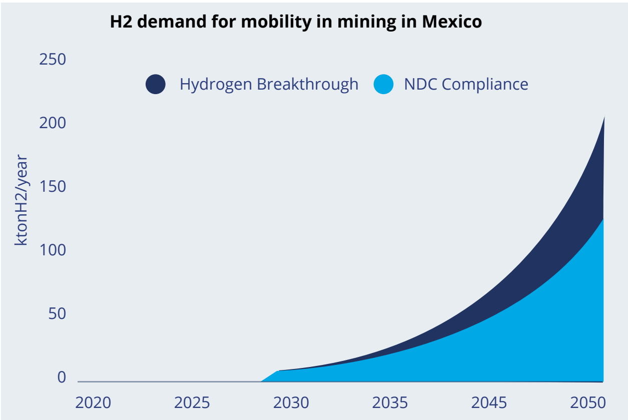
Figure 4. 2. Projected TCO over a 10-year lifetime for diesel and hydrogen fuel cell CAEX in NDC Compliance and Hydrogen Breakthrough scenarios



[9]FCHEA, A Case for Hydrogen to Decarbonize Mining, 2020.

Figure 4.3. Hydrogen demand for haul trucks in Mexico in NDC Compliance and Hydrogen Breakthrough scenarios.By mid-century, the diesel alternative will be 20 times more expensive than the hydrogen one, and green hydrogen production and filling systems will be broadly adopted in mines. By then, up to 75% of the mining truck fleet in Mexico would be powered by hydrogen, with the remaining 25% of the fleet being diesel CAEX ending their useful life. This results in a national hydrogen demand of over 200 kilotons per year and more than 2,400 MW of electrolysis installed for mines.

Figure 4. 3. Hydrogen demand for haul trucks in Mexico in NDC Compliance and Hydrogen Breakthrough scenarios.

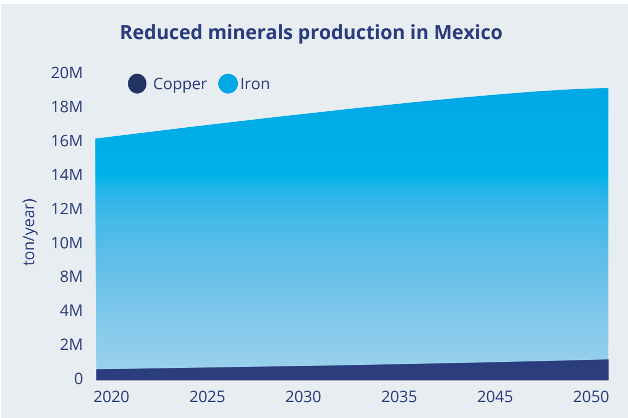


4.2. Mineral Reduction

4.2.1. Mineral reduction hydrogen demand

The minerals considered for potential reduction with hydrogen in Mexico are iron and copper, with over 94% of the volume considered being used for iron for steel production. The growth of reduction gas volume demanded is assumed to be proportional to the combined mineral production of such metals in Mexico, for which projections to 2050 were made as shown in Figure 4.4.

Figure 4. 4. Projected production of reduced minerals considered in Mexico in 2020-2050. Source: Hinicio with data from CAMIMEX[10].

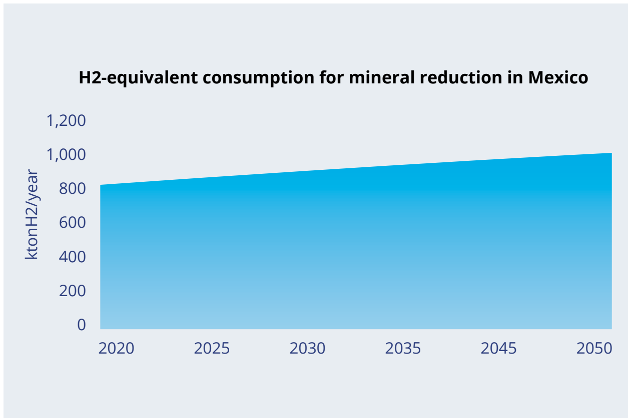


The production of steel has two main technology routes, both of which present opportunities to be decarbonized with the use of green hydrogen. The first one is by blast furnace (BF), where hydrogen could partially replace coal coke to react with limestone and the iron ore before it continues to a basic oxygen furnace once in the form of reduced molten iron. This process accounts for nearly two-thirds of global steel production and has pilots for integrating hydrogen in Europe and Asia.

The second route happens by the direct reduction of the iron ore with syn-gas obtained from natural gas, which could have increasing shares of green hydrogen up to a full replacement, or 100% H2, before proceeding to the electric arc furnace (EAF). This second process for obtaining direct reduced iron (DRI), also known as DRI-EAF, represents a smaller fraction of global steel production but if fed by green hydrogen it could be a more viable solution to decarbonize steel in the short and medium terms, with ongoing pilots from steel majors across Europe.

Considering hydrogen's reactivity, between 50 and 68 kilograms would be required for every ton of mineral reduced, according to industry literature[11]. Potentially substituting all the mineral reductants with hydrogen would require up to a million tons of hydrogen per year by 2050, as shown in Figure 4.5, for which only a small fraction is expected to be demanded even in the more favorable Hydrogen Breakthrough scenario.

Figure 4. 5. Projected maximum H2-equivalent demand for mineral reduction 2020-2050, based on hydrogen's potential as a reactant



4.2.2. Green hydrogen demand for mineral reduction

To assess the economic competitiveness of green hydrogen for mineral reduction, the cost for every ton of ore reduced was estimated and projected to 2050 with assumptions from both scenarios providing the basis to be compared with natural gas for this application, on a cost per reactant unit basis. The demand of green hydrogen was calculated as a share of the total requirement of reductant to be substituted.

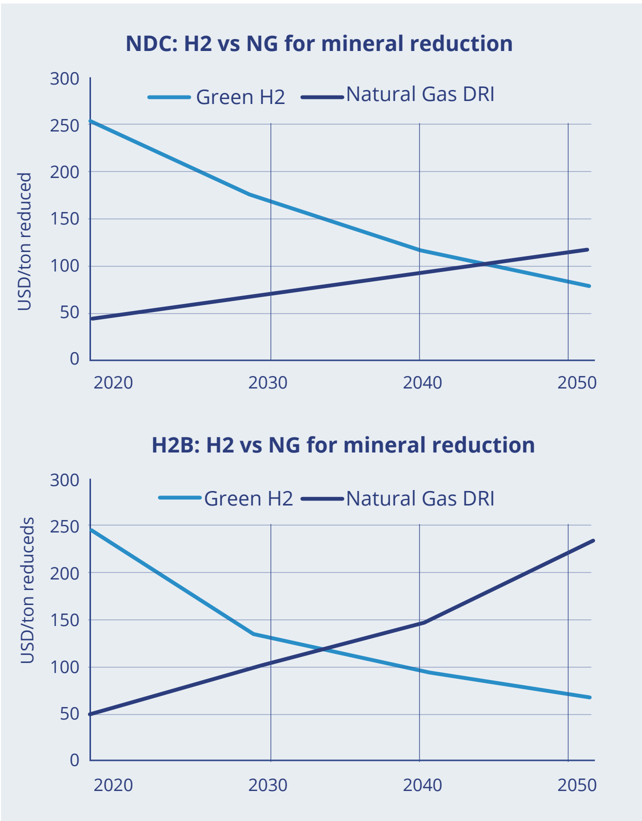
[10]CAMIMEX: Mining Chamber of Mexico
[11]Midrex Technologies, Inc., Hydrogen Uses in Ironmaking, 2018.

NDC Compliance

In 2030 the reduction of minerals using hydrogen will be far from being an economically viable process, so there will only be demonstrative projects of multinational companies with corporate decarbonization goals and with an interest in green hydrogen. The emissions reduction goals of the mining sector may be met through alternative technologies such as CCUS.

By 2050, mineral reduction with green hydrogen has been economically competitive for less than a decade. In a scenario with more solid capacities for the production and installation of electrolysis systems, there will be an accelerated adoption of green hydrogen for this application, however it will not exceed 10% of the mineral reduction capacity in Mexico. This share of mineral reduction with hydrogen could make the full contribution of reducing emissions to comply with the NDC for this industry by 2050.

Figure 4. 6. Projected cost evolution of reducing minerals with hydrogen and natural gas, in both NDC Compliance and Hydrogen Breakthrough scenarios .



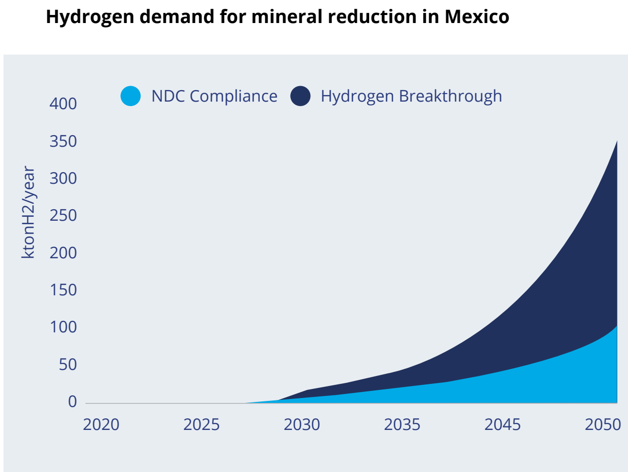
Hydrogen Breakthrough

By 2030 green hydrogen is still 30% more expensive than natural gas as an alternative for mineral reduction, however it is known that its break-even point will occur a few years later, and demonstration and small-scale projects will be deployed for up to 60MW of electrolysis for this application, demanding 4,500 tons of hydrogen per year.

[12]Columbia Center on Sustainable Investment, "The Renewable Power of the Mine", 2018.

In 2050 the reduction of minerals through the use of green hydrogen would have at least 15 years of being economically profitable compared to natural gas and up to 25% of the minerals reduced in Mexico could use green hydrogen, mainly in the steel sector. This major use of hydrogen as a reductant would demand 250,000 tons of green hydrogen per year, requiring an installed electrolysis capacity of 2.9 GW. This would represent the largest opportunity for green hydrogen in the mining and metals, industry, accounting for roughly half of the total demand of the segment by midcentury..

Figure 4. 7. Hydrogen demand for mineral reduction in Mexico in NDC Compliance and Hydrogen Breakthrough scenarios



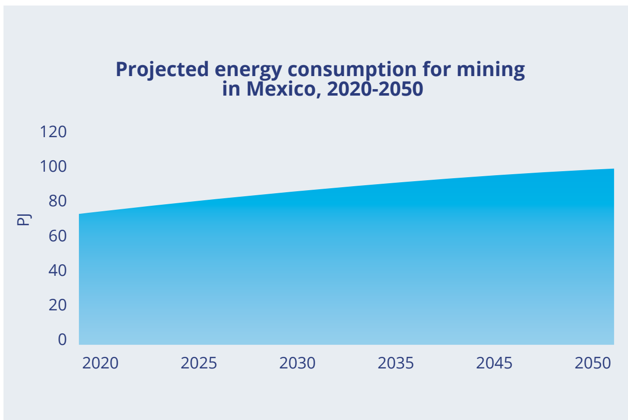
4.3. Thermal applications in mining

4.3.1. A thermal applications hydrogen demand in mining

Today, energy produced and procured by mining companies is mostly fossil fuel based and energy consumption for mining is rising with a growth in demand from minerals and the decline of ore grades, with an expected increase of 36% globally from 2020 to 2035.

In Mexico, the energy consumption of the sector is tracked in the National Energy Balance, representing a reported 3.8% of all industrial energy consumption in the country in 2017.

Figure 4.8. Projected energy consumption for the mining sector in Mexico for 2020-2050. Source: Hinicio



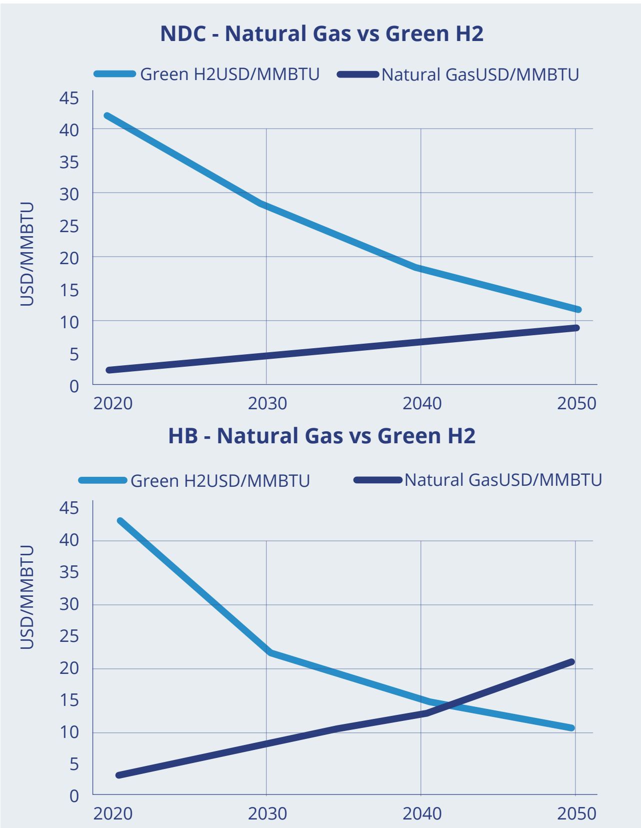
The iron and steel industry reported a share of the national energy consumption of13.2%, yielding a combined demand with mining of around 320 petajoules of energy consumed in 2017[13]. Both steel production routes, blast furnace and DRI-EAF, also consume high-temperature heat which is currently supplied from the combustion of fossil fuels, with a large share of it coming from coal at a global level; which poses a large potential to be replaced with emissions-free green hydrogen[14].

To account for the fuel demand which could potentially be reduced by hydrogen, the study focuses on the energy produced from oil and natural gas with projections made based on historical data published on the National Energy Balance and following a trend similar to the preceding decade towards 2050, as shown in Figure 4.8.

4.3.2. Green hydrogen demand for thermal applications in mining

A large potential for green hydrogen lies in the substitution of natural gas in thermal applications in the mining industry, which are currently powered by fossil resources, with natural gas representing 17% of their total energy consumption according to the National Energy Balance. The cost of the energy supplied was projected for both hydrogen and natural gas on a per-energy unit basis for comparing cost competitiveness.

Figure 4. 9. Projected cost evolution of the energy supplied by hydrogen and natural gas, in both NDC Compliance and Hydrogen Breakthrough scenarios..

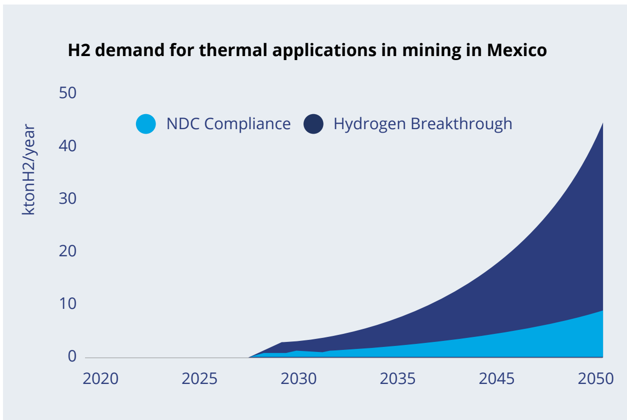


NDC Compliance

In 2030, the mining sector will be highly electrified following an existing trend where nearly two thirds of the sector's energy consumption were already electric power as early as 2019 as reported by SENER. Compliance with the segment's NDCs could be supported with migration to renewable energy and leaving little room for other low-carbon solutions such as hydrogen, which will still be four times more costly than natural gas for energy generation in 2030. By this year, there will only be low-capacity pilot projects that demonstrate the technical feasibility of hydrogen technology in the sector.

By 2050, although it will be very close, hydrogen will still not be economically competitive for this scenario in most of the country, resulting in a relatively low deployment compared to other applications with less than one twentieth of the sector's hydrogen demand. Projects for thermal applications of H2 will still be present in regions of high renewable potential and where hydrogen can be integrated into different uses at the same site, i.e., combining mobility with heat demand. Green hydrogen in thermal-mining applications will replace a maximum of 10% of the sector's natural gas consumption, demanding 9,000 tons of hydrogen per year by midcentury and requiring a capacity of 100 MW to be installed nationwide.

Figure 4. 10. Hydrogen demand for thermal applications in mining in Mexico for NDC Compliance and Hydrogen Breakthrough scenarios



Hydrogen Breakthrough

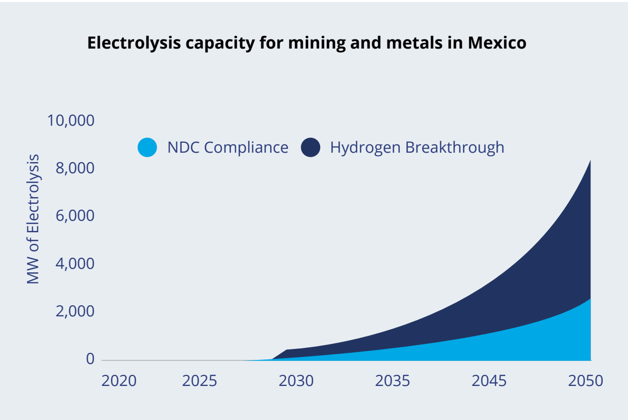
Green hydrogen will not be competitive in 2030 compared to natural gas in thermal applications, still being over twice as costly. In part due to the electrification of the sector, only the first demonstration projects to use green H_2 for heat in mines will be seen, possibly sharing green H_2 production with pilots of mobility applications, demanding roughly over a thousand tons per year by then.

[13]Ministry of Energy, National Energy Balance 2017.
[14]IEA, Iron and Steel Technology Roadmap, 2020.

4.4. Conclusions for hydrogen in the mining and metal industry

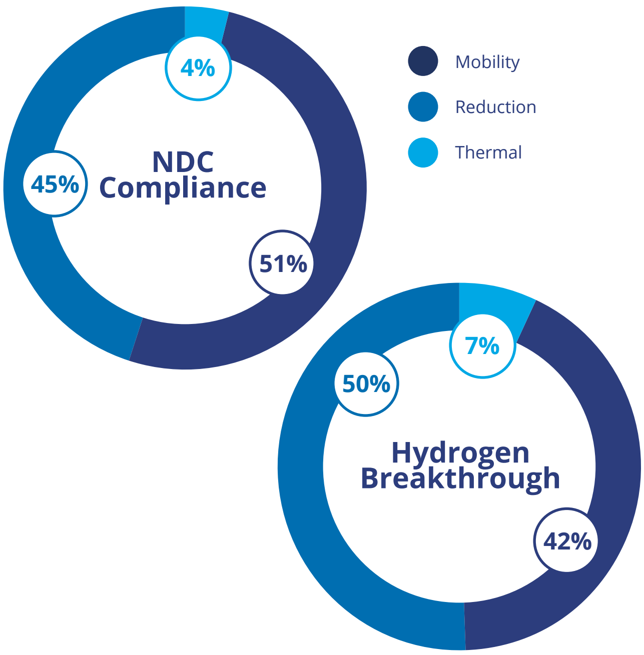
Hydrogen demand in both scenarios will remain low before 2030, and deployments will begin broadening in that decade as FC CAEX come online and mineral reduction applications become competitive. Demand will rise at an accelerated rate in the Hydrogen Breakthrough scenario along with electrolysis capacity installed, however it will remain more moderate in the NDC Compliance scenario where it will not achieve economic competitiveness by 2050.

Figure 4. 11. Electrolysis capacity projections for the mining and metals industry in Mexico for NDC Compliance and Hydrogen Breakthrough scenarios



For both scenarios, thermal applications will represent a small share of the hydrogen demand, while hydrogen-powered mobility in mines and mineral reduction will each consume large and similar shares of hydrogen by 2050, as shown in Figure 4.12.

Figure 4. 12. Hare of hydrogen demand by end-use in the mining and metals industry by 2050 for NDC Compliance and Hydrogen Breakthrough scenarios.



5. Opportunities in green hydrogen for the cement industry

Cement is the key ingredient in concrete, the most widely used man-made material. Cement has a large carbon footprint accounting for about 8% of the global GHG emissions, being higher than all individual countries except for China and the US. This makes cement the second largest emitter of CO2 and the third largest energy consumer among industrial sectors worldwide[15].

> This makes cement the second largest emitter of CO2 and the third largest energy consumer among industrial sectors worldwide.

The cement industry has already made advancements in decarbonization through energy efficiency and the combustion of biomass and waste materials. In the last few decades, this has led to a decline of 18% in the emissions per ton produced. However, these measures alone can only decarbonize a fraction of the cement production process. The part of the cement-making process that generates the most emissions is the production of "clinker", an intermediate product and the main component of cement made up of calcium silicates, which requires the use of enormous kilns (large, rotating ovens) at temperatures above 1,400 °C that demand large quantities of energy, usually supplied by fossil resources. Thermal uses account for around 40% of the emissions associated with cement production, and partial substitution of conventional fuels by green hydrogen could provide a route to aid in decarbonizing the sector[16]. Pilot projects are already underway by large cement players in partnership with companies in energy, industrial gases, hydrogen equipment, carbon capture, among other.

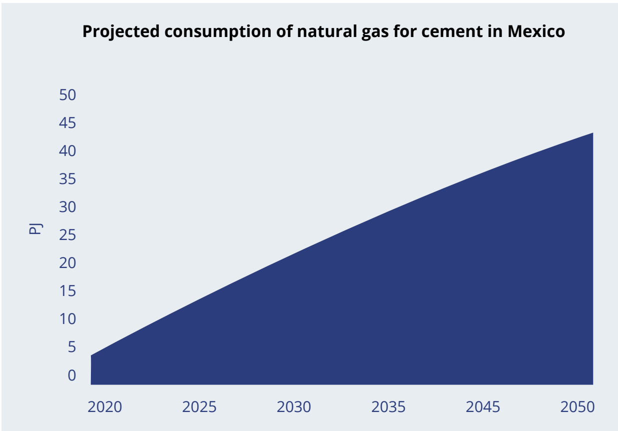
In Mexico, four technology routes have been identified by SEMARNAT to reduce emissions in the sector[17]: increase the share of alternative fuels for thermal consumption, which are mostly solid waste but could as well be replaced by hydrogen; substitution of clinker for other cementing materials; carbon capture, use, and sequestration (CCUS); and substitution of petroleum coke with natural gas in the kilns.

[15]IEA, Technology Roadmap - Low-Carbon Transition in the Cement Industry, France, 2018.
[16]Chatham House, Making Concrete Change Innovation in Low-carbon Cement and Concrete. UK, 2018.
[17]SEMARNAT, Mexico: Sixth National Communication and Second Biennial Report of Update before the UNFCCC. Mexico, 2018.

5.1. Hydrogen demand for the cement industry to 2050

The cement industry's main energy source in Mexico is petroleum coke, supplying nearly two thirds of the demand in 2018, followed by electricity with 22% of the energy demand, and finally an 11% shared between coal and natural gas as reported in the National Energy Balance. One of the decarbonization routes for the sector to comply with Mexico's NDCs is to substitute petroleum coke with natural gas, a less carbon-intensive fossil fuel. Including a share of hydrogen into the new fuel mix could contribute to further reducing carbon emissions and it could be the gateway to introduce hydrogen into other cement applications. Thus, the potential demand for hydrogen would be proportional to the increase in the share of natural gas, which is currently constrained by cost competitiveness. A measure proposed for decarbonizing the segment suggests that by 2030, 15% of the petroleum coke could be substituted by natural gas, as reported by the Mexican government to the UNFCCC. Following a similar trend, the share could reach 32% of the projected coke consumption by 2050, resulting in the natural gas demand evolution shown in Figure 5.1. This gradual substitution of petroleum coke by natural gas is assumed for both scenarios.

Figure 5. 1. Projected consumption of natural gas for the cement industry in Mexico in 2020-2050. Hinicio projection based on goals by SEMARNAT.



Additionally, a study by the Mineral Products Association in the UK suggests that the flame produced by burning only hydrogen could lack enough heat to make it adequate for the formation of clinker, so it could be used in combination with natural gas or biomass in an effort to combust low carbon fuels only, thus only partial substitution by hydrogen could be considered.

5.2.Projected green hydrogen demand the cement industry

Cost-competitiveness is assessed comparing hydrogen to natural gas for thermal energy production, due to natural gas being the direct projected fuel to be substituted for this application. The cost-curves to be considered are the same as those for thermal applications in the mining and metals industry, shown in Figure 4.9, which indicate that cost parity is achieved in 2042 in the Hydrogen Breakthrough scenario and after 2050 under NDC Compliance assumptions.

NDC Compliance

By 2030, the vast majority of the energy consumption from the cement sector still comes from petroleum coke, with 15% being substituted by natural gas out of which only a negligible fraction is hydrogen for early tests of the technology. The cement sector must make use of alternatives such as improvement of performance and heat reuse from the kilns and other measures such as introducing more biomass as fuel to comply with its NDCs targets for 2030.

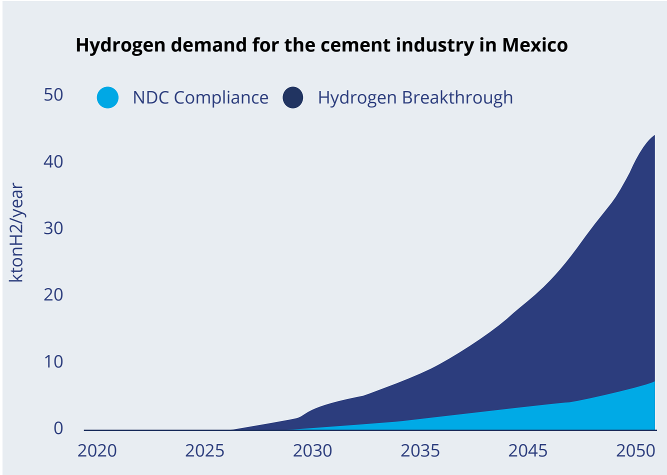
In 2050, green hydrogen production will be closer to cost-competitiveness with natural gas, so a larger amount could be used instead of natural gas for heat applications in the cement industry. However, it will still not be economically competitive, therefore only 2% of the natural gas will be replaced by hydrogen, yielding a reduced demand of only 7,000 tons per year by 2050. This covers small-scale or pilot projects adding up to 80 MW of electrolysis capacity. In this scenario, the NDCs for the industrial sector by 2050 are set at 11.3%, of which hydrogen could contribute up to 3.7%.

Hydrogen Breakthrough

Under this scenario, early pilot projects will be starting to be implemented in 2026. By 2030 hydrogen will remain twice as costly as natural gas for this application, but growing interest to decarbonize the sector will allow up to 20 MW of electrolysers to be deployed. Deployment will grow six-fold during the following decade, as the substitution of petroleum coke with natural gas increases as well as the share of hydrogen in the mix.

By 2050, an average of up to 10% of the energy delivered by natural gas for cement in the country could be green hydrogen, which is around 3% of the sector's total. This would amount to a demand of 36,000 tons of hydrogen supplying 4.3 PJ of energy per year, requiring and installed capacity of nearly 420 MW dedicated to the cement industry alone.

Figure 5. 2. Hydrogen demand for the cement industry in Mexico for NDC Compliance and Hydrogen Breakthrough scenarios

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6. Opportunities for green hydrogen for the chemical industry

Currently most of the hydrogen consumed worldwide is used as a feedstock for industry, with only a small share going to energy generation or mobility applications. The chemical sector is the largest consumer of industrial energy and of oil and gas, out of which around half is consumed as a raw material and the other half is used for energy[18]. Chemicals are also the third largest emitting industry, only after iron & steel and cement. Green hydrogen could help decarbonize both uses as an energy source and as a chemical feedstock. Some of these industries have been consuming hydrogen for decades and are among the first potential adopters of green hydrogen given their experience, infrastructure readiness, and established demand for this industrial gas.

In Mexico, most of the hydrogen demand is consumed by PEMEX in oil refining and for producing ammonia for fertilizers. However, other industries consume gray hydrogen as a feedstock including the making of flat glass, synthetic resins, and margarines, which are the segments subject of analysis in this section. The beforementioned uses of hydrogen for oil refining, ammonia, methanol, and other synthetic fuels have been addressed in the report on "Opportunities for state-owned companies PEMEX & CFE".

The hydrogen applications considered in this report for the chemical industry are divided in two end-use categories: **energy applications** and **industry feedstock**, which includes flat glass, synthetic resins, and margarines..

6.1. Energy applications in the chemical industry

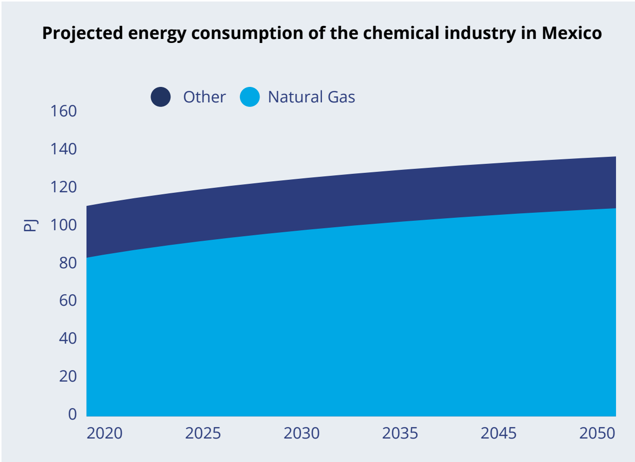
6.1.1. Energy applications hydrogen demand in the chemical industry

Today, the energy procured by the chemical industry is mostly fossil-based. In Mexico, around three-quarters of the energy comes from natural gas and one tenth from other fossil fuels, leaving the remaining small fraction of it to electric power consumption[19].

[18]IEA, Chemicals. Francia, 2020.
[19]SENER, Energy Balance 2018. Mexico, 2020.

Natural gas demand is expected to rise along with the industry's growth and cover a larger share of the energy currently supplied by other fossil fuels, projecting to reach close to 90% of the industry's energy by 2050. Energy supplied by natural gas is the most feasible to adopt green hydrogen as a co-fuel. The possibility of increasing the percentage of hydrogen content in the blend with natural gas could contribute gradually to supply more than 100 PJ per year of the energy demanded by the sector in mid-century, as shown in Figure 6.1.

Figure 6. 1. Projected energy consumption for the chemical industry in Mexico for 2020-2050. Source: Hinicio



6.1.2.Green hydrogen demand for energy applications in the chemical industry

Cost-competitiveness is assessed comparing it to natural gas for thermal energy production, being the fuel that it is projected to directly substitute for this application. The cost-curves and main drivers for adoption of green H2 to be considered are the same as those for thermal applications in the mining and metals industry, as well as cement, as shown in Figure 4.9. These projections indicate that cost parity is achieved in 2042 in the Hydrogen Breakthrough scenario and after 2050 under NDC compliance assumptions..

NDC Compliance

By 2030, green hydrogen is nearly five times more costly than natural gas. Yet, driven by climate goals, early tests begin to replace 0.05% of energy supplied by natural gas adding to 5 MW of electrolysis and a hydrogen demand of 400 tons per year and slowly increasing to reach 35 MW in 2040.

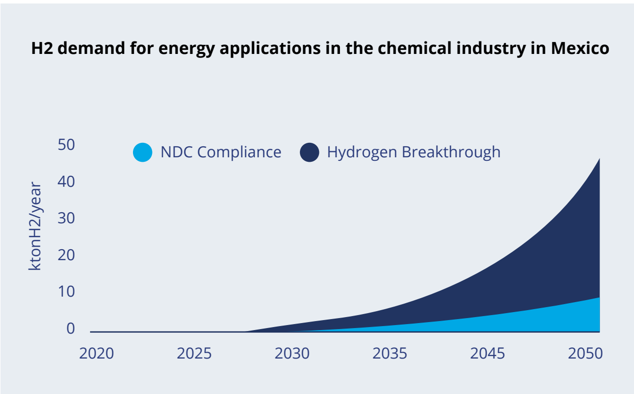
In 2050, in preparation for an approaching technological change at a broader scale, the industry has begun a wider deployment of green hydrogen as an energy molecule through demonstration projects. Green hydrogen projects in thermal applications will represent around 1% of the sector's energy demand but given the industry's size this will represent nearly 9,000 tons of hydrogen per year and an electrolysis capacity above 100 MW. The NDCs of the chemical industry will be achieved through other technological improvements to their current systems or the electrification of their processes.

Hydrogen Breakthrough

The economic competitiveness of green hydrogen with gas will occur until the 2040's, so the adoption in 2030 of this gas in the chemical industry will only be through pilot projects. In 2030 the pilot projects that could be deployed will range from a few MW of electrolysis to a few dozen of them with a yearly consumption of 3,000 tons per year. The companies that could adopt hydrogen as an energy source will be mainly those that obtain it as a by-product or those that have more than one consumption application of it.

By 2050, with already 8 years of economic competitiveness of green hydrogen versus natural gas, the deployment of electrolysis for hydrogen in thermal applications could be up to 500 MW, which would represent a 5% replacement of natural gas in the sector and demand 45,000 tons of hydrogen per year. The 5% replacement of fossil fuels in the chemical sector would demand more than 40% of hydrogen's contribution to the NDCs this year.

Figure 6. 2. Hydrogen demand for energy applications in the chemical industry in Mexico for NDC Compliance and Hydrogen Breakthrough scenarios

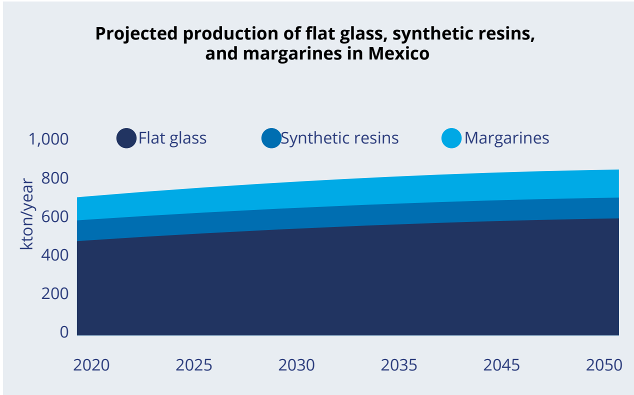


6.2. Hydrogen as feedstock for the chemical industry

6.2.1. Hydrogen demand as feedstock for the chemical industry

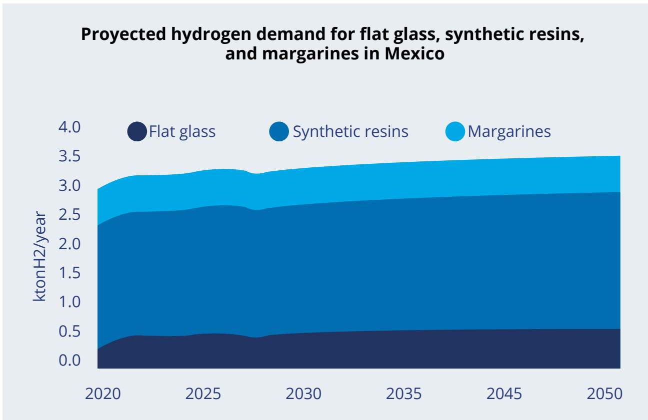
The hydrogen consuming industries identified in Mexico and considered in this analysis are flat glass, synthetic resins, and margarines. To estimate the potential green hydrogen market, the growth in hydrogen demand for each material is assumed to be proportional to the increase of the output for each of the products by weight, each requiring different proportions of hydrogen in their manufacture: 1.26 kg of hydrogen for each ton of glass produced, 5 kg of hydrogen per ton of margarines, and a much higher 20.3 kg of hydrogen per ton of synthetic resins. The projected production for the materials adds up to 670 tons per year combined in 2020 and is projected to reach over 800 tons by 2050, as shown in Figure 6.3.

Figure 6. 3. Projected production of flat glass, synthetic resins, and margarines in Mexico in 2020-2050.



Since only a few kilograms of hydrogen are required for each ton of the materials produced, the resulting projected hydrogen demand is low compared to other segments, at only 3,500 tons per year by 2050, as seen in Figure 6.4. Even if all the demand were to be supplied by green hydrogen, the potential market to be addressed would be constrained in size.

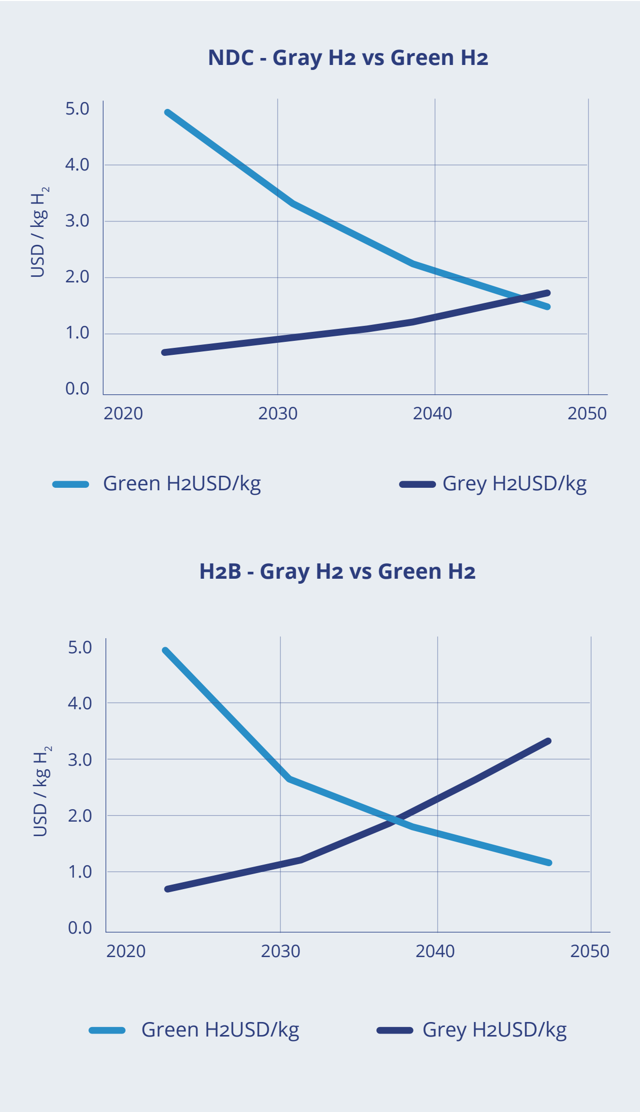
Figure 6. 4. Projected hydrogen demand for the manufacture of flat glass, synthetic resins,and margarines in Mexico in 2020-2050.



6.2.2. Green hydrogen demand as feedstock for the chemical industry

Green hydrogen as a chemical feedstock has the challenge of competing directly with gray hydrogen in terms of cost. No new uses for hydrogen are considered but rather the substitution of a share of the gray hydrogen currently supplied with green hydrogen. The cost curves for both scenarios are displayed in Figure 6.5, which show that green hydrogen reaches cost parity very close to 2050 in the NDC Compliance scenario, and around 2036 for Hydrogen Breakthrough.

Figure 6. 5. Projected cost evolution of gray and green hydrogen, in both NDC Compliance and Hydrogen Breakthrough scenarios.

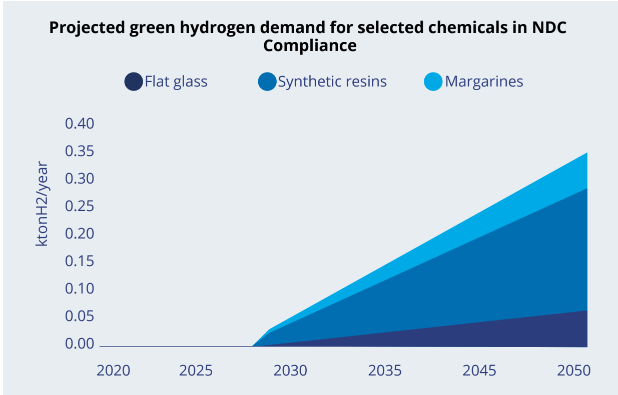


NDC Compliance

Green hydrogen will start being introduced in 2030 in low volumes with slightly growing shares reaching up to 10% of the total hydrogen demand by 2050. Because of its late competitiveness occurring towards the end of the 2040's, green hydrogen will not have a broad penetration, reaching 1 MW of electrolysis demand until 2034, and will likely be focused on processes that require high purity hydrogen for their activities or that have limited supply of conventional hydrogen. By 2050, the green hydrogen demand will be of only 350 tons per year and required a total of 4 MW of electrolysis spread in pilot projects around the country.

It must be noted that given the small amounts relative to other sectors and end-sues, the resulting volumes are in the order of decimals of thousand tons per year, the unit used throughout this report.

Figure 6. 6. Projected green hydrogen demand for flat glass, synthetic resins, and margarines 2020-2050 in NDC Compliance scenario.

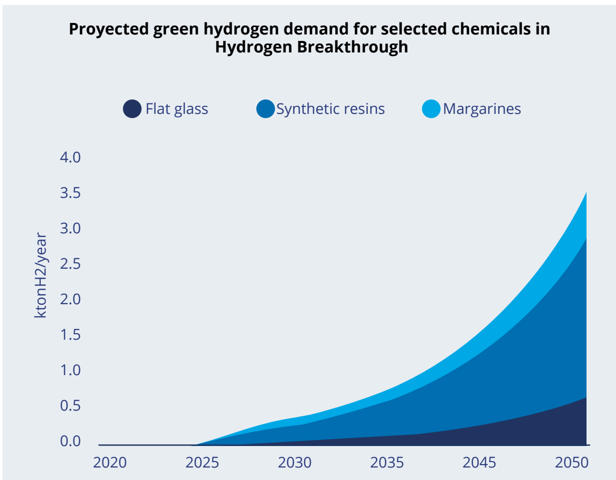


Hydrogen Breakthrough

In a scenario with a very favorable development for green hydrogen technologies, it will reach its competitiveness against gray hydrogen in the mid-2030's. Even if in small volumes, the introduction of green hydrogen will be significantly more accelerated than in NDC Compliance scenario. Green hydrogen will be first introduced in pilot projects in 2026 and by 2030 it will represent 10% of the hydrogen supplied, comparable with NDC Compliance scenario's demand for mid-century.

Green hydrogen will achieve cost parity in 2036 and further accelerate its deployment, accounting for nearly a third of the hydrogen demand and potentially a full substitution by 2050. In this year, with well over a decade of full economic competitiveness, low consumption volumes and decentralized utilization sites, green hydrogen has the potential to replace up to 100% of the consumption of gray hydrogen as a raw material in the chemical industry, driven by climate, cost, and supply concerns. Therefore, by mid-century, around 40 MW of electrolysis could be required to supply the 3,500 tons of hydrogen demanded each year by the studied industries, as displayed in Figure 6.7.

Figure 6. 7. Projected green hydrogen demand for flat glass, synthetic resins, and margarines 2020-2050 in Hydrogen Breakthrough scenario



7. Opportunities for green hydrogen with water desalination

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 liters/kgH2 as efficiencies improve.

Demand for green hydrogen in Mexico in the Hydrogen Breakthrough scenario will amount to around 18 GW of electrolysis by 2050. The hydrogen uses considered include oil refining, ammonia production, synthetic fuels, injection in the natural gas grid, and power generation by mixing with natural gas in CCGT's as studied in the report of this series focused in PEMEX and CFE; and for the private sector in the mining and metals industry, cement, and chemical industry, which are analyzed in this report. Such installed capacity would consume up to 17.3 hm3 of water[20], representing just 0.006% of the current consumption of water in Mexico.

Even though this is a small requirement, tapping freshwater resources is not always possible in certain locations in Mexico where the resource is scarce, such as the northwest. In such regions, water desalination will be required for hydrogen production.

A geographical analysis of the Mexican territory shows that the highest solar potential areas have the lowest water availability, suggesting the potential need for sea water desalination to supply hydrogen production needs.

The region of Baja California will most likely rely on sea water desalination to meet its demands for electrolysis water. As described in the report on opportunities for hydrogen in integration of renewable energy into the grid of this series, Mulegé, Baja California, could demand approximately 2,800 tons of hydrogen in 2050 (produced with a 33 MW electrolysis plant), which represents a water consumption of 0.03 hm3/year. Desalination of this amount of water for the Mulegé system represents a small challenge given the typical capacity of desalination plants that ranges from 7 thousand to 400 thousand m3 per day, or 2.56 to 14.6 hm3/year, the smaller accounting for 85 times the Mulegé hydrogen project's water demand with a single unit. A small plant of 7,000 m3 per day, equivalent to 2.56 hm3/year, could meet the demand for hydrogen in energy storage, and other hydrogen uses in the region. The size of the investment of this kind of plants ranges the 30 - 35 million USD.

Considering the water requirement for electolysis of the Mulegé system (0.03 hm3/year for 33 MW of electrolysis) and the investment cost of the desalination plants (11.7 million dollars per hm3/year) we can obtain a parametric value of 10,640 USD of investment in desalination plants of seawater per MW of water-demanding electrolysis. 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.

Given today's uncertainty over future electrolysis plants' locations, it is not possible to quantify the potential needs for water desalination in the country at this stage. This analysis should be conducted case by case as projects begin to emerge.

Figure 7. 1. Maps of precipitation of Mexico

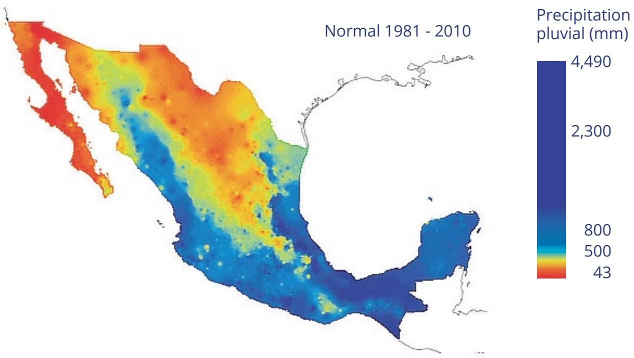
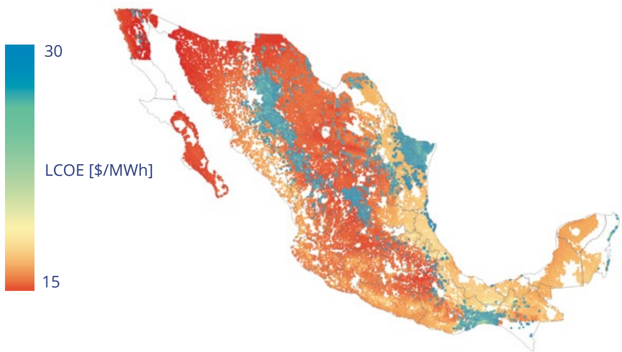


Figure 7. 2. Maps of cost of electricity of Mexico.



[20]hm3: cubic hectometer, one is equal to a thousand million liters (1hm3 = 10^9 l)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8. Conclusions

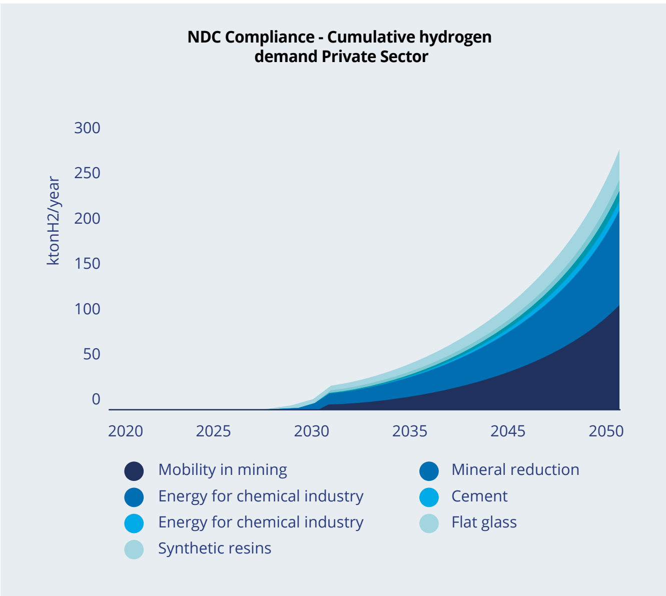
NDC Compliance

Among the segments studied, **the mining sector presents the largest opportunities for green hydrogen, especially for mobility** where it is already close to cost competitiveness, **as well as for mineral reduction applications.** The area of opportunity that follows in size is found in supplying energy to the chemical industry from green hydrogen instead of fossil fuels, mainly substituting natural gas.

Hydrogen uses for thermal applications in the mining and cement industries will be of a smaller scale, while opportunities as a chemical feedstock for flat glass, synthetic resins, and margarines will be negligible comparable to the national green hydrogen market.

In 2030 demand will have reached 14,000 tons of hydrogen per year, requiring over 160 MW of electrolysis capacity installed, and will grow at a slow but steady rate until mid-century, as economic competitiveness is achieved or close to be achieved for all end uses. **By 2050** the cumulative green hydrogen demand for all applications for the private sector will be of **280 kilotons per year** and require an **electrolyser capacity of 3,250 MW**. At this moment, the green hydrogen market in Mexico will have a value of **420 million dollars** annually.

Figure 8. 1. Projected hydrogen demand for all end uses. Opportunities for private sector in Mexico. NDC Compliance scenario..



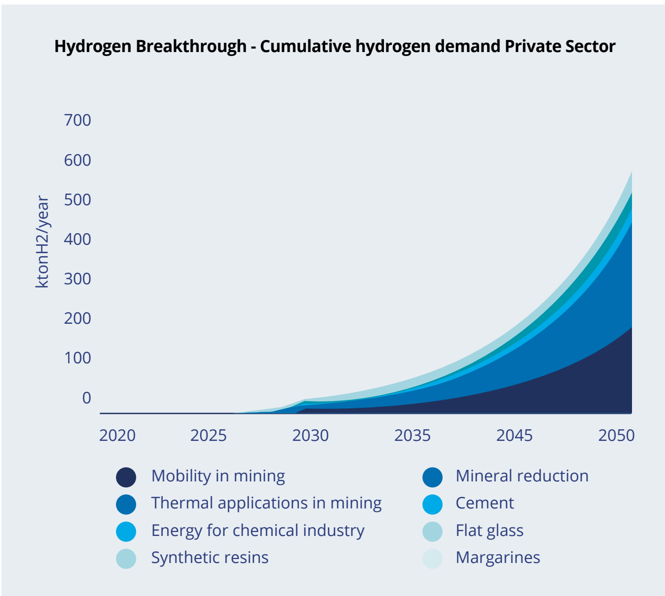
Hydrogen Breakthrough

Similar to NDC Compliance, **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, mining, and cement industries, 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 8. 2. Projected hydrogen demand for all end uses. Opportunities for the private sector in Mexico. Hydrogen Breakthrough scenario.



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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 fuels' 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). NCD 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 CO2 by 2050.
Sectors demand forecast	• The study uses official projections for the available sectors (Refining, Transportation fuels, and Thermal Plants capacity) • 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.
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.

Consideration	Description
Levelized Cost of Electricity (LCOE)	• LCOE for solar PV was calculated using the following consideration: - CAPEX 2050: 320 USD/kWh - OOPEX: 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
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 H2 - 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 H2 - Stack Lifetime 2050: 80,000 hours
Green hydrogen penetration	• For both scenarios, green hydrogen penetration was calculated consid-ering 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
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 gray or green) was calculated with information reported in the Statistical Year-book 2016 of PEMEX and hydrogen production reported by the same year in the White -book of Hydrogen Supply for the Tula Refinery (2018). Estimated hydrogen consumption is 0.75 kg H2 per crude oil barrel. • 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 gray-green hydrogen Is reached in 2047: the market share of green hydrogen 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 gray 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 gray and green hydrogen is reached by 2038. • With 12 years of economic competitiveness, green hydrogen has developed a 2.4 GW of electrolysis by 2050, replacing 50% of gray hydrogen from refineries in Mexico.

	Ammonia
Common considerations	• It has been identified as a decreasing trend in ammonia production from 2010 to 2019, being cero in 2019. • Considering that PEMEX has a reported capacity of ammonia production of 4633 k ton NH3/year and new contracts of natural gas supply are being signed by state-owned companies in Mexico: is expected a recovery in the production of ammonia. 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, 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 H2 per ton of ammonia.
NDC Compliance	• Green hydrogen is not yet economically competitive over gray 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. • Considering that 12 years of economic breakeven between gray and green hydrogen has elapsed by 2050, the installed capacity of electrolysis would represent 60% of hydrogen for ammonia production.

Synthetic fuels

Common considerations

- The Levelized Cost of Synthetic Fuels was calculated with Hinicio'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.
- 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)
  - CO2: 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.

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

Common considerations

- According to SENER projection of natural gas demand and This study calculations, 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 H2/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
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. • 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 Volume 2 of this consultancy are taken into consideration.
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. • By 2050 less than 500 MW of electrolysis 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 cheaper 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.