Assessment of the greenhouse gas mitigation potential of green hydrogen. An implementation roadmap for Mexico

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1. Introduction

The need to find alternatives for the decarbonisation of the world economies has positioned hydrogen (H_2) as an attractive solution for bringing greenhouse gas (GHG) emission reductions and energy security. The versatility of hydrogen has promoted projects targeting all areas of energy consumption (mobility, heat in buildings and the industry, power generation) and as a feedstock in industry (refining, chemical, iron and steel, mining). These applications are emerging, and their adoption is accelerating around the world as decarbonisation efforts towards net-zero emissions strengthen. However, hydrogen decarbonisation efforts in the long run will need a strong commitment to invest in zero-carbon hydrogen production and use from 2020 to 2035, so that costs can be reduced. Between 2035 and 2050, structural shifts based on available and near-mature technology need to emerge, and research and development efforts for hydrogen production and use must continue so that between 2050 zero-carbon H_2 production and use are widespread in areas such as heavy industries (Rissman, et al., 2020). The International Energy Agency (IEA) (2020) expects a substantial increase in hydrogen and hydrogen-related products (hydrogen, ammonia, synthetic fuels, electricity from hydrogen, among others) between 2019 and 2070, with a demand for hydrogen-related energy sources 12 times higher in comparison to oil and gas. Moreover, hydrogen and hydrogen-based fuels may account for 8% of global CO_2 emission reductions (6% from transport and 2% from industry).

For the latter reasons, it is vital to promote technologies and policies to give shape to a rapid adoption and development of hydrogen solutions based on a careful assessment of each potential project. As an important member of the international community, Mexico cannot stay behind these efforts and must increase the promotion and adoption of green hydrogen. The generation, transport, storage, distribution, and use of green hydrogen in Mexico could represent an opportunity for not only reducing GHG emissions but for increasing the energy security of the country and taking advantage of its vast renewable resources. Green hydrogen in Mexico could also bring new job opportunities and the reduction of atmospheric pollutant emissions. The IEA (2021) considers that low-carbon hydrogen could represent the next step for Latin America's clean energy transition reaching sectors that are not feasible for direct electrification. While it is considered that hydrogen will be required for decarbonising the transport sector of the entire region, the potential for decarbonising heavy industry would be concentrated in few countries such as Mexico. The study highlights the fact that there are still significant challenges for low-carbon hydrogen in the region, but it is recommended that the initial efforts to be focused on research and development, pilot projects and their preparation for a large-scale deployment. Recommendations for policy makers include the definition of the long-term role of hydrogen in the energy system; the identification of opportunities for the development of key technologies, the support of early financing schemes and the reduction of investment risk; focus on research and development; the use of certification schemes to incentivise production of low-carbon hydrogen and the regional cooperation and the positioning of Latin America in the global landscape (IEA, 2021a).

The potential for green hydrogen in Mexico is high and initial estimates by Hinicio (2021) consider that the country has the total potential to install 22 TW of electrolyser capacity by 2050. Furthermore, green hydrogen could avoid the emission of 40 $MtCO_2e$ per year and create 90,000 new jobs by 2050. In addition to this, it was also estimated that the levelised cost of hydrogen (LCOH) could be between 2.55 US Dollars per kg in 2030 and 1.22 US Dollars per kg in 2050. Hinicio (2021) considers that the largest opportunities for green hydrogen are within the transport sector, and particularly for public transport buses and freight trucks. The production of synthetic fuels for the aviation industry is another area of application for green hydrogen meeting 12% of the aviation's fuel demand by 2050. In the case of industry, it is considered that the mining industry could use green hydrogen for fuelling mining vehicles and for steel production and thermal applications. According to the study, PEMEX and CFE are other important players that could serve as initial adopters of green hydrogen in the production of ammonia and for oil refining. Finally, thermal applications in the chemical industry and for cement production was also considered having a moderate participation. Mexico could also become an important exporter to Europa and particularly to the United States and could closely compete with Chile and Australia (Hinicio, 2021).

The geographical location of Mexico not only provides vast renewable resources but also provides a unique commercial position that has not been fully exploited yet. Green hydrogen is a technological alternative that could bring environmental, social, and economic benefits. However, to adopt this alternative, more efforts are still required to bring together all the interested actors and adopt a common strategy. The interest in green hydrogen in Mexico is relatively new and this work complements the existing work regarding the estimation of the greenhouse gas mitigation potential of hydrogen and tis costs. However, it takes a different perspective by focusing on the potential demand of green hydrogen and specific alternatives for implementing a pilot project considering commercially available technologies and scales. The objective of the project was to estimate the GHG mitigation potential and costs for green hydrogen in Mexico and design an implementation roadmap for demonstrative projects.

2. Methodology

To accomplish the previously mentioned objectives, the project was divided into three main parts, which consisted of a thorough review of the state-of-the-art technologies, including existing projects around the world. This information was also complemented with a review of existing costs. The second part of the project was aimed at using the information generated from the first part to estimate the potential demand for hydrogen of pilot projects, the renewable energy system requirements to meet this demand and the mitigation of GHG emissions and the levelised cost of hydrogen (LCOH) for the analysed alternatives. The analysis of projects was focused on including the largest number of alternatives as possible. The following list presents these alternatives.

- Oil refining. The six refineries of the National Refining System: “Ing. Antonio M. Amor” Refinery, in Salamanca, Guanajuato; “Francisco I. Madero” Refinery, in Ciudad Madero, Tamaulipas; “Ing. Antonio Dovalí Jaime” Refinery, in Salina Cruz, Oaxaca; “Ing. Héctor R. Lara Sosa” Refinery, in Cadereyta, Nuevo León; “Miguel Hidalgo” Refinery, in Tula de Allende, Hidalgo; and “Gral. Lázaro Cárdenas del Río” Refinery, in Minatitlán, Veracruz.
- Mining. Ten mines were analysed, nine of them were open pit mines and one was an underground mine. The analysed mines were: Peñasquito and Aranzazú, in Zacatecas; Los Filos, in Guerrero; La Herradura, Buenavista del Cobre, La Caridad, Mulatos and Piedras Verdes, in Sonora; and Dolores and Pinos Altos, in Chihuahua.
- Public transport. Public transport alternatives were analysed in three cities including the Ecovía system in Monterrey, the Mi Macro system in Guadalajara and the Metrobús system in Mexico City.
- Natural gas grid injection. The analysed nodes were: node V030 “GLORIADIOS”, in Chihuahua; node V036 “INYMONCLOVA”, in Coahuila, node V059 “MAREOFGRAFO”, in Nuevo León, node V061 “RAMONES”, in Tamaulipas, y node V918 “ELCASTILLOINY” in Jalisco.
- Industry. Three sectors were analysed including methanol production (PEMEX Independencia Petrochemical Complex in Puebla), ammonia production (PEMEX Cosoleacaque Petrochemical Complex in Veracruz and GPO Ammonia Plant in Sinaloa) and steel production (ArcelorMittal in Michoacán and Ternium in Puebla).

For the refineries of the National Refining System, two alternatives were considered. In the first case, the total hydrogen demand of each refinery was estimated while in the second case, the hydrogen demand for increasing the current use of desulphurisation units for intermediate distillates was considered. In the latter case, the increase was estimated considering the utilisation level of existing primary distillation units, so that existing production of hydrogen could be complemented with green hydrogen. The hydrogen demand in both cases was determined with information from Petróleos Mexicanos (PEMEX) regarding the hydrogen consumption of the refinery process units, oil product production reports and real refinery process diagrams.

In the mining sector, the 9 mines in which a significant part of their activities correspond to open-cast mining were chosen because of the characteristics of their mining vehicle fleets and the magnitude of their diesel consumption. In the case of the underground mine, it was included in the analysis due to the importance of its production in the national context. For this sector, two cases were evaluated as well. In the first case, the potential hydrogen demand of the entire fleet of mining vehicles running on fuel cells was considered. The second case considered a demonstration project and the amount of hydrogen required to operate one mining diesel vehicle retrofitted with a fuel cell. The calculation of the hydrogen demand was carried out based on the current estimated diesel consumption of the fleet of mining vehicles of each mine, using vehicle fleet data and typical usage patterns, and assuming a fuel cell efficiency of 60%, an electric motor efficiency of 85% and an efficiency for internal combustion engines of 30%.

In the transportation sector, the use of green hydrogen in fuel cell electric vehicles (FCEV) was analysed for the BRT systems of the three largest cities in Mexico: Guadalajara, Monterrey, and Mexico City. The first case considered the implementation of fuel cell buses in the entire fleet of the systems, including expansion projects underway or planned in the future. Similarly, demonstration projects were considered, in which the renewable hydrogen production systems were designed to supply the demand of one unit in the only line in operation (Ecovia, Monterrey, Mi Macro, Guadalajara), in the expansion project (Mi Macro, Guadalajara), or in the largest line of the system (Metrobus, CDMx). Current BRT fossil fuel consumption and hydrogen demand were estimated using real data regarding the fuel economy of vehicles and with data from official sources regarding the number of units and the travelled distance.

For the injection of green hydrogen into the natural gas grid, it was assumed that it was possible to add up to 3% of hydrogen by volume of the total transported gas, considering the selected injection points. The analysis was carried out in 5 injection nodes of the Integrated National Natural Gas Transport and Storage System (SISTRANGAS). The inclusion parameters include the demand for natural gas in the regions of interest, in the domestic, commercial, and industrial sectors, as well as the available solar potential. To estimate the amount of hydrogen required to inject into the nodes, information from National Gas Control Center (CENAGAS) was used. Maps of renewable resources from the Ministry of Energy (SENER) were also consulted.

Finally, for the industrial sector, projects were evaluated for the use of hydrogen in the production of ammonia, methanol, and steel. For ammonia, two facilities and two alternatives for the demand of hydrogen were evaluated. In the first case, a 50 tonne per day ammonia production was considered while in the second case a 300 tonne per day ammonia production was considered. In the case of methanol, the only production facility in the country was analysed, considering a hydrogen demand of 6,400 tonnes per year. In the case of steelmaking, two of the largest production facilities were included. The hydrogen demand to be supplied was just over 20,000 tonnes per year (for one production module) and 3,202 tonnes per year, respectively.

The hydrogen demand was used to estimate the size of the renewable energy systems required to generate the electricity for the electrolysers. The analysis of the proposed systems was based on the use of HOMER which was developed by the US National renewable Energy Laboratory (NREL) for the design and optimisation of distributed generation systems (HOMER Energy, 2021). This software specialises in hybrid energy systems and has been extensively used for different kinds of systems. The model incorporates the hydrogen demand, the natural resources, and the technical and economic characteristics of the equipment. The software simulates the alternatives hourly and minimises the costs for several possible configurations and estimates the LCOH. The electricity generation systems considered technical and economic data adjusted to several scales and were primarily based on solar photovoltaic (PV) technology. However, the feasibility of wind and solar PV hybrid systems and wind systems were considered for the refineries of Madero and Salina Cruz due to the availability of larger wind resources in these areas. The analysed electrolysis system considered PEM electrolysers because of their flexibility to cope with the variability imposed by renewable intermittent electricity systems. For this technology, technical and economic data was also included and adjusted for different scales, as well. Storage for the generated hydrogen in these systems was also part of the calculations and it was assumed that it was possible to provide a continuous supply and the in-situ storage. For this reason, additional compressors were not considered. The calculations used solar and wind resource information in the existing sites. This information was obtained from the National Solar Radiation Database (NSRDB), published by NREL.

The analysed cases explore the possibility of generating and using the hydrogen in-situ. In this manner, transport costs are avoided. However, it is not always possible to find suitable areas for renewable energy generation because of the existence of protected areas, human settlements, or other terrain conditions. In addition to this, the demand for hydrogen in certain applications can be high which requires a high amount of energy. Solar and wind projects require large areas of land and for this reason it is necessary to find suitable places. Some of the sectors analyse demonstrative small-scale projects which can be implemented at the same places where hydrogen is used. However, larger scale projects require a more detailed analysis of the area requirements. For this, the information from the National Atlas of Zones with a High Potential of Clean Energy (AZAEL) published by the Secretariat of Energy (SENER) was used. This information considers the inclination of the terrain, human settlements, altitude, protected areas, geological climate areas with risk, communication and transport infrastructure and water bodies (SENER, 2017). Areas for agriculture were not considered and for this reason, maps from the National Institute for Geography and Statistics (INEGI) were used. In the cases with no available space, renewable systems had to be in distant locations, and it was necessary to consider transport costs. The estimation of the GHG mitigation potential was based on the consideration of the traditional systems that produce hydrogen (through methane steam reforming) or the substitution in the use of diesel or natural gas.

The final part of the project had the objective of designing a roadmap for the implementation of pilot projects based on the existing case studies that were documented during the literature review. In this section, estimated timelines for the implementation of renewable energy and hydrogen projects were included, in addition to the evaluation of the social and economic conditions of the potential location of selected pilot projects. Finally, barriers and opportunities were highlighted together with recommendations for the implementation of a project. Based on this, the following section presents the applications of the methodology and the main results of the project.

3. Results

The following table presents the main results from the analysis of the various alternatives and cases for hydrogen demand. However, it must be highlighted that the GHG emissions that could be reduced go from 1.3 million tCO_2e per year for the smaller scale projects to 5.6 million tCO_2e per year for the total hydrogen demand of the analysed systems. The largest emission reduction potential was found for oil refining. The LCOH for the demonstrative projects goes from 5.54 US Dollars/kg (Salina Cruz Refinery) to 8.55 US Dollars/kg (Ecovía Monterrey). The impact of transport depends on the project and the location of the renewable energy system, but costs can increase up to 50%. Additionally, the LCOH is highly dependent on the availability of renewable resources and thus in the location of the projects. In the case of wind energy or hybrid systems they had higher costs in comparison to solar PV systems.

Table 3.1. Green hydrogen analysis results.

Project	System configuration	Production of H_2 (tonnes/year)	Initial investment (Million US Dollars)	Levelised cost of H_2 (US Dollars/kg)	Levelised cost of H_2 considering transport (US Dollars/kg)	CO_2 emission reductions (tonnes/year)
Oil Refining						
Refinery/case study						
Salina Cruz/total demand case	PV system: 543.8 MW Electrolyser: 312 MW Tank: 44 tonnes	16,188.2	917.9	5.53	5.6	149,902.7
Salina Cruz/HID case	PV system: 1,906.3 MW Electrolyser: 1,100 MW Tank: 155 tonnes	56,921.3	3,227.2	5.53	5.55	527,091.2
Salina Cruz/total demand case, wind system	Wind energy system: 400 MW Electrolyser: 250 MW Tank: 355 tonnes Rectifier: 250 MW	16,450.1	1,161.1	7.46	In situ	152,327.9
Madero/total demand case, hybrid system	PV system: 385 MW Wind energy system: 120 MW Electrolyser: 225 MW Tank: 75 tonnes Rectifier: 95 MW	16,191.0	875.6	5.61	In situ	149,928.7
Madero/total demand case	PV system: 765.6 MW Electrolyser: 385 MW Tank: 95 tonnes	18,095.8	1,232.6	6.64	6.73	167,567.1
Madero/HID case	PV system: 239.8 MW Electrolyser: 125 MW Tank: 30 tonnes	5,757.9	392.7	6.65	6.74	53,318.2
Madero/total demand case, wind system	Wind energy system: 1,069.3 MW Electrolyser: 385 MW Tank: 275 tonnes Rectifier: 385 MW	18,248.5	2,273.6	13.30	In situ	168,981.1

Madero/total demand case, hybrid system	PV system: 600 MW Wind energy system: 117.5 MW Electrolyser: 350 MW Tank: 70 tonnes Rectifier: 100 MW	18,115.8	1,225.0	7	In situ	167,752.3
Tula/total demand case	PV system: 426.93 MW Electrolyser: 254 MW Tank: 45 tonnes	12,793.9	739.7	5.63	5.96	118,471.5
Tula/HID case	PV system: 1,338 MW Electrolyser: 800 MW Tank: 145 tonnes	40,238.4	2,326.2	5.63	5.96	372,607.6
Cadereyta/total demand case	PV system: 1,254.7 MW Electrolyser: 695 MW Tank: 215 tonnes	32,819.2	2,146.4	6.37	6.5	303,905.8
Cadereyta/HID case	PV system: 850.3 MW Electrolyser: 485 MW Tank: 140 tonnes	22,502.1	1,471.6	6.37	6.5	208,369.4
Minatitlán/total demand case	PV system: 2,279.2 MW Electrolyser: 1,115 MW Tank: 280 tonnes	51,204.9	3,622.7	6.90	6.91	474,157.4
Minatitlán/HID case	PV system: 191.3 MW Electrolyser: 92 MW Tank: 23 tonnes	4,260.8	302.0	6.92	6.98	39,455.0
Salamanca/total demand case	PV system: 542.2 MW Electrolyser: 330 MW Tank: 55 tonnes	17,248.1	948.9	5.35	5.51	159,717.4
Salamanca/HID case	PV system: 17.5 MW Electrolyser: 10.8 MW Tank: 1.6 tonnes	555.0	32.4	5.71	7.21	5,139.3
Mining						
Mine/case study						
Peñasquito/total demand	PV system: 874 MW Electrolyser: 505 MW Tank: 80 tonnes	26,591.2	1,485.6	5.44	In situ	394,795
Peñasquito/demo project	PV system: 3.2 MW Electrolyser: 1.66 MW Tank: 265 kg	90.8	6.2	6.7 6	In situ	1,328
Los Filos/total demand	PV system: 149.5 MW Electrolyser: 90 MW Tank: 11 tonnes	4,590.5	258.4	5.48	5.54	68,154.0
Los Filos/demo project	PV system: 3 MW Electrolyser: 1.59 MW Tank: 220 kg	87.3	5.9	6.77	In situ	1,278

Pinos Altos-Creston Mascota/total demand	PV system: 26.8 MW Electrolyser: 16 MW Tank: 3.5 tonnes	777.0	48.4	6.1	7.65	11,525
Pinos Altos-Creston Mascota/demo project	PV system: 3.71 MW Electrolyser: 1.74 MW Tank: 370 kg	89.0	6.7	7.45	In situ	1,303
Mulatos/total demand	PV system: 42.3 MW Electrolyser: 24.5 MW Tank: 5 tonnes	1,207.3	74 .1	6.01	7.51	17,928
Mulatos/demo project	PV system: 3.41 MW Electrolyser: 1.71 MW Tank: 370 kg	89.0	6.5	7.21	In situ	1,303
Dolores/total demand	PV system: 76.6 MW Electrolyser: 45 MW Tank: 10 tonnes	2,228.1	134.1	5.9	8.87	33,060
Dolores/demo project	PV system: 3.62 MW Electrolyser: 1.84 MW Tank: 320 kg	89.0	6.8	7.56	In situ	1,303
Aranzazú/total demand	PV system: 16 MW Electrolyser: 9.6 MW Tank: 1.75 tonnes	499.3	29.5	5.79	6.55	7,450
Aranzazú/demo project	PV system: 3.11 MW Electrolyser: 1.62 MW Tank: 270 kg	89.1	6.0	6.77	In situ	1,303
Piedras Verdes/total demand	PV system: 192.2 MW Electrolyser: 115 MW Tank: 20 tonnes	5,716.9	333.8	5.68	In situ	84,884
Piedras Verdes/demo project	PV system: 3.34 MW Electrolyser: 1.67 MW Tank: 270 kg	89.0	6.3	7.02	In situ	1,303
Buenavista del cobre/total demand	PV system: 1,078.1 MW Electrolyser: 660 MW Tank: 110 tonnes	32,993.5	1,892.7	5.58	5.64	489,862
Buenavista del cobre/demo project	PV system: 3.23 MW Electrolyser: 1.71 MW Tank: 340 kg	89.0	6.3	7.08	In situ	1,303
La Caridad/total demand	PV system: 218 MW Electrolyser: 135 MW Tank: 25 tonnes	6,660.2	386.5	5.65	5.73	98,884
La Caridad/demo project	PV system: 3.2 MW Electrolyser: 1.7 MW Tank: 330 kg	89.0	6.3	7.03	In situ	1,303

La Herradura/total demand	PV system: 829.2 MW Electrolyser: 505 MW Tank: 80 tonnes	26,060.5	1,449.3	5.41	In situ	386,958
La Herradura/demo project	PV system: 2.04 MW Electrolyser: 1.31 MW Tank: 210 kg	65.6	4.7	7.34	In situ	959
Public transport						
System/case study						
Ecovía Monterrey/total demand	PV system: 40.5 MW Electrolyser: 22.2 MW Tank: 7.4 tonnes	1,055.6	70.66	6.55	7.24	2,824
Ecovía Monterrey/demo project	PV system: 0.5 MW Electrolyser: 0.28 MW Tank: 95 kg	13.2	1.1	8.55	in situ	35.18
Mi Macro Guadalajara/total demand, Calzada+Periférico	PV system: 151.2 MW Electrolyser: 90 MW Tank: 12 tonnes	4,659.9	260.3	5.44	5.63	67,427
Mi Macro Guadalajara/demo project, Calzada	PV system: 0.5 MW Electrolyser: 0.3 MW Tank: 40 kg	15.4	1.12	7.4	in situ	222.7
Mi Macro Guadalajara/demo project, Periférico	PV system: 1.24 MW Electrolyser: 0.76 MW Tank: 115 kg	38.5	2.8	7.41	in situ	556.74
Metrobús, CDMX/total demand, 7 Lines + Line 0	PV system: 312.5 MW Electrolyser: 185 MW Tank: 25 tonnes	9,549.1	535.6	5.47	5.6	123,619
Metrobús, CDMX/demo project, Line 1	PV system: 0.44 MW Electrolyser: 0.27 MW Tank: 50 kg	13.2	1	7.71	in situ	170.02
Hydrogen injection into natural gas grid						
Injection Node/case study						
V030 GLORIADIOS/3 % Vol. Injection	PV system: 55 MW Electrolyser: 34.3 MW Tank: 6.3 tonnes	1,572.9	99.2	6.15	6.51	47,048
V036 INYMONCLOVA/3 % Vol. Injection	PV system: 7 MW Electrolyser: 4.1 MW Tank: 0.8 tonnes	204.3	13.8	6.61	In situ	6,105
V059 MAREOGRAFO/3 % Vol. Injection	PV system: 11.2 MW Electrolyser: 6.3 MW Tank: 1.9 tonnes	297.7	21	6.9	In situ	8,901

V061 RAMONES/3 % Vol. Injection	PV system: 2,029.2 MW Electrolyser: 1,115 MW Tank: 210 tons	52,338.3	3,380	6.29	6.3	1,566,731
V918 ELCASTILLOINY/3 % Vol. Injection	PV system: 49 MW Electrolyser: 28.3 MW Tank: 4.3 tons	1,463.4	84.5	5.66	6.12	43,762
Industry						
Project/sector/case study						
Topolobampo/Ammonia/300 t/day system	PV system: 573.7 MW Electrolyser: 343 MW Tank: 53 tonnes	17,517	992.1	5.51	5.57	162,211
Topolobampo/Ammonia/50 t/day system	PV system: 96.1 MW Electrolyser: 57 MW Tank: 9 tonnes	2,921.8	166.6	5.55	5.78	27,056
Cosoleacaque/Ammonia/300 t/day system	PV system: 771.9 MW Electrolyser: 384 MW Tank: 97 tonnes	17,523	1237.4	6.89	6.95	162,263
Cosoleacaque/Ammonia/50 t/day system	PV system: 118.3 MW Electrolyser: 70 MW Tank: 24 tonnes	2,921.2	211.8	7.06	7.75	27,050
Independencia Petrochemical Complex/methanol/6,400 tonnes/year production facility	PV system: 212.5 MW Electrolyser: 124 MW Tank: 21 tonnes	6,400	363.9	5.54	5.61	59,264
Acelormittal/steelmaking/one module H_2 demand	PV system: 725 MW Electrolyser: 405 MW Tank: 55 tonnes	20,729.8	1,205.8	5.67	5.73	275,298
Ternium/steelmaking/ 3,202 tonnes/year demand	PV system: 105.2 MW Electrolyser: 63 MW Tank: 10 tonnes	3,202.1	183.1	5.57	6.59	29,651

HID: hydrodesulphurisation of intermediate distillates

The projects presented above correspond to the main areas for the use of hydrogen in Mexico. In the case of the oil refining industry, it was found that the utilisation of hydrodesulphurization units particularly to produce diesel is low. This industry can benefit from the use of green hydrogen not only for reducing GHG emission but by producing larger amounts of low sulphur diesel which has been insufficient for meeting the required standards. Mining is another important area of application due to the potential use of green hydrogen as a fuel. Due to the increasing costs of diesel, it is possible that the cost of green hydrogen can be lower in comparison to diesel in the following decades. Transportation, according to the literature is another important area for the use of green hydrogen which es expected to be adopted first. Industry is another important application for green hydrogen and this compound can achieve GHG emission reductions in sectors that are difficult to electrify. Finally, in the case of green hydrogen injection into the natural gas grid, there are still some challenges regarding the existing transport and distribution pipeline materials and final use equipment which still need to be solved. However, given the current geopolitical situation and the experience in Europe in this area, this alternative may become an important manner to use green hydrogen and to export it to other countries, particularly to the United States. Green hydrogen opportunities in Mexico are larger in the central and particularly the northern states of Mexico. Sonora, Nuevo León, Tamaulipas, Chihuahua, Coahuila, Guanajuato, Jalisco, Zacatecas, Puebla, and Veracruz were the identified states with the largest potential due to their current and potential hydrogen demand.

As presented previously, there are several opportunities for the implementation of a pilot project in Mexico. The installation of solar PV systems is relatively fast, as it involves simple connections of the panels in arrays and mounting in metallic structures. The operation and maintenance (O&M) requirements of solar PV are simple and low-cost (Boston Strategies International, 2016).

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