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Egypt’s Low Carbon Hydrogen Development Prospects

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Ali Habib, Energy Consultant

Mostefa Ouki, Senior Research Fellow, OIES

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Preface

There has been rapidly growing global interest in the last two years about the potential role of hydrogen in a decarbonised energy system. Much of what has been written has been rather high level and often quite aspirational. At the Oxford Institute for Energy Studies, we believe it is important to examine the facts behind the rhetoric and to make a realistic assessment of how the future energy economy might evolve. For decarbonisation in general and for hydrogen in particular, it is clear that individual countries and sectors will follow their own pathways, depending on their specific circumstances. This paper by Ali Habib and Mostefa Ouki therefore provides a timely and detailed examination of the prospects for potential hydrogen development in Egypt. As one of the larger industrial economies in the Middle East, Egypt already has a large grey hydrogen production, estimated by the authors at around 1.8 million tonnes per year, spread across fertiliser, refining, steel and petrochemicals, emitting nearly 20 million tonnes of CO_2 per year.

In recent years, Egypt has been expanding its renewable energy capacity, although it still remains less than 10 percent of total power generation. It has significant potential for further expansion of renewables, with a target to reach over 40 percent of installed capacity by 2035. This, combined with concerns about potential future natural gas supplies, leads to a focus on hydrogen from electrolysis ("green" hydrogen) rather than from natural gas with carbon capture and storage ("blue" hydrogen). The paper examines these alternatives and their associated costs and challenges in some detail. It also highlights the policy changes which would be needed in order to make an economic case for investment in production of lower-carbon hydrogen. The paper concludes that while there is significant potential for low carbon hydrogen, this potential will take time to materialize, most likely beyond 2030 before large-scale production is seen. However, it also makes the case that Egypt's preparation for this low carbon hydrogen journey should start in earnest in the near term and be based on realistic, clear, and achievable milestones.

As well as providing a detailed examination of the situation for hydrogen in Egypt, the paper also provides a useful case study which can help inform other countries considering development of a low-carbon hydrogen strategy.

Martin Lambert
Head of Hydrogen Research
Energy Transition Research Initiative
Oxford Institute for Energy Studies

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Introduction

Egypt has one of the largest economies in the Middle East and North Africa (MENA) region and several of its industries are large sources of greenhouse gas (GHG) emissions. As part of its contribution to mitigate GHG emissions within the framework of the 2015 Paris Agreement on climate change, Egypt is focusing on the development of an ambitious renewable energy program.

Some of Egypt's main industries are big consumers of hydrogen which is produced locally using indigenous natural gas without abatement of the CO_2 emissions resulting from this production process. In the long-term, the production and consumption of this unabated hydrogen, known as grey hydrogen, could become a serious challenge for Egypt's exports of manufactured products. Thus, the Egyptian government is planning to develop low carbon hydrogen alternatives and has set up an inter-ministerial committee to prepare a national hydrogen strategy for Egypt.

It is interesting to note that Egypt is one of the first countries in the MENA region to have produced and used green hydrogen. In 1960, the Egyptian Chemical Industries (KIMA) company started producing green hydrogen using hydroelectricity supplies from the nearby Aswan dam to produce green ammonia (Choksi *et al.*, 1980). However, when the KIMA plant was rehabilitated and expanded in 2019, green hydrogen production through electrolysis was stopped and KIMA switched to the production of grey hydrogen using the gas-based steam methane reforming process (Brown, 2019).

Looking at a much wider scope of hydrogen utilization within Egypt, this paper explores the prospects for low carbon hydrogen developments in Egypt, focusing on the potential replacement of Egypt's large domestic production of grey hydrogen with cleaner low carbon hydrogen alternatives.

The paper starts with an overview of Egypt's two key energy subsectors, natural gas and power, that are critical to the potential development of low carbon hydrogen supplies. It is followed by an assessment of Egypt's hydrogen market. A hydrogen production cost analysis is then presented to estimate hydrogen production costs and how these costs could vary according to different scenarios and assumptions. Before presenting its conclusions, the paper highlights the series of challenges Egypt would face in the implementation of low carbon hydrogen development plans.

Energy sector overview

The potential production of low carbon hydrogen (blue hydrogen or green hydrogen or both) in Egypt will be driven by medium to long-term developments in the country's power and natural gas energy subsectors. Thus, it is important to outline first the key challenges and opportunities facing these two key energy segments of Egypt's economy.

Power sector

Egypt's power sector is dominated by the state-controlled Egyptian Electricity Holding Company (EEHC) and its affiliated companies. In 2000, EEHC was incorporated as a joint-stock company. The activities of production, transportation, and distribution of electricity were separated and six production companies, one transmission company, and nine distribution companies were created. EEHC owns a controlling share of 51 per cent in each of these affiliated companies.

In 2018/2019, Egypt's total installed electricity generation capacity was 58.4 GW and the peak load was 31.4 GW. With an installed generation capacity of nearly double the current peak load, Egypt is working hard to export and/or expand its electricity supplies to neighboring countries.

Over the last four years, the average annual increase in installed capacity was 14 per cent. The largest power capacity additions took place between 2016/2017 and 2017/2018. This increase of 22 per cent reflects the commissioning in 2017/2018 of the three Siemens combined cycle gas turbine (CCGT) power plants with a total generation capacity of 14,400 MW (EEHC, 2020).

As shown in Table 1, CCGT and steam power plants account for 84 per cent of Egypt's total installed power capacity with CCGT units representing about 56 per cent of this capacity. Egypt's power sector relies heavily on natural gas as a generation fuel. Presently, gas accounts for over 90 per cent of all the electricity generated (EEHC, 2020). In 2018/2019, a total of 199,843 GWh was generated in Egypt, mostly from thermal power plants.

Table 1: Egypt's Installed Power Capacity: 2014/20215 – 2018/2019[1] (MW)

Description	2014/2015	2015/2016	2016/2017	2017/2018	2018/2019
CCGT	11,880	12,630	12,630	30,030	32,470
Steam	15,082	14,798	15,449	15,449	16,749
Open Cycle Gas	4,874	7,845	13,345	5,745[2]	4,055
Hydro	2,800	2,800	2,800	2,832	2,832
Renewables (solar and wind)	687	887	887	1,157	2,247
Total	**35,323**	**38,960**	**45,111**	**55,213**	**58,353**

source: EEHC, 2020

Variable renewable energy sources or VRE (solar and wind) represent a small share of Egypt's installed generation capacity. In 2018/2019, they represented only about 4 per cent of the country's installed capacity. A modest share, when also considering the intermittency of these renewable sources of electricity generation. However, over the last five years, Egypt recorded an over four-fold increase of its renewable energy capacity from about 690 MW in 2014/2015 to 3,150 MW in 2019/2020. This is the result of government policies supporting the development of renewable energy and efforts to significantly increase the share of renewable energy sources in the country's electricity generation mix.

Egypt is planning for renewable energy sources to achieve a 42 per cent share of the country's total installed power capacity by 2035. Egypt's renewable energy (excluding hydro) capacity is projected to increase from 3.2 GW in 2020 to 54 GW by 2035. This targeted renewable energy capacity portfolio would consist of 21 GW of wind, 17 GW of solar photovoltaic (PV), 11 GW of concentrated solar power (CSP), and about 5 GW of biomass capacities (RCREEE, 2020). Egypt's renewable energy program is led by the New and Renewable Energy Authority (NREA). NREA was established in 1986 and is responsible for renewable energy development in Egypt.[3]

The global trend of declining electricity generation costs of renewable energy, especially in the MENA region, would help Egypt expand its renewable energy potential. Reflecting this trend, the prices of electricity generated from solar and wind projects in Egypt have been reduced. The lowest announced solar energy bid price of US$ 27.75 per MWh was announced in September 2018 for the deployment of a 200 MW Independent Power Producer (IPP) solar energy power plant in Upper Egypt's Kom Ombo area to be developed by the Saudi power developer ACWA Power. More recent bid prices have not been publicly announced, but according to the NREA, current electricity prices for solar and wind projects in Egypt are between US$ 20 per MWh and US$ 30 per MWh, respectively (Egypt Today, 2021).

The current electricity price for industrial usage at medium voltage (11-22 kVA) is around US$ 72 per MWh which is much higher than the current electricity generation price of renewable energy plus the cost of its transmission, which varies between US$ 2.03 and US$6.77 per MWh[4] depending on the voltage level used.

If Egypt is to pursue its announced target of 54 GW of renewable energy by 2035, it is likely to face a difficult challenge regarding electricity grid flexibility. Assuming a 3 per cent average annual growth rate, the peak load requirement by 2035 is estimated to reach about 50 GW. Thus, under favorable

[1] There are no disaggregated data on installed power capacity presently available beyond 2018/2019.
[2] Large drop in gas power plants capacity is due to reclassification to combined cycle power plants
[3] http://nrea.gov.eg/test/en/Home
[4] Exchange rate used is 16 EGP/US$

conditions, renewable energy could cover large parts of Egypt's electricity consumption or even cover the full consumption during off-peak periods. However, under unfavorable conditions for the generation of electricity from renewable sources of energy, the grid must have the required resilience to adjust to an adverse situation. Furthermore, if there is a sudden loss of a large renewable energy power plant, the grid is required to be ready and have a contingency for this scenario. This situation requires a highly flexible electricity supply system.

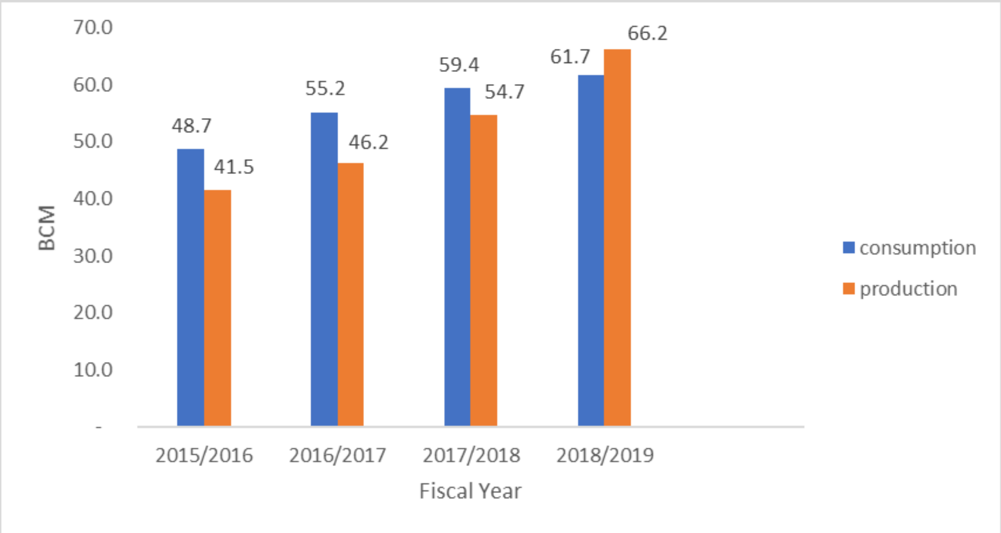
Therefore, the potential development of green hydrogen projects, which will require large renewable sources of electricity supplies, would depend first on how the above-mentioned challenges/opportunities of expanding substantially the share of renewable energy would be addressed. Second, it would also depend on how much surplus renewable energy capacity would be available and when, to develop Egypt's long-term green hydrogen potential.

Natural gas sector

Egypt could also consider the potential production of another category of low carbon hydrogen, blue hydrogen, using natural gas and carbon capture and storage (CCS) or carbon capture storage and utilization (CCUS) technology. This subsection presents an overview of Egypt's natural gas potential.

During the last decade, Egypt's natural gas balance faced some severe challenges resulting in gas shortages, as shown in the figure below, and the inevitable recourse to gas imports.

Figure 1: Egypt's Natural Gas Balance: 2014/2015 – 2018/2019



Source: EGAS, 2020

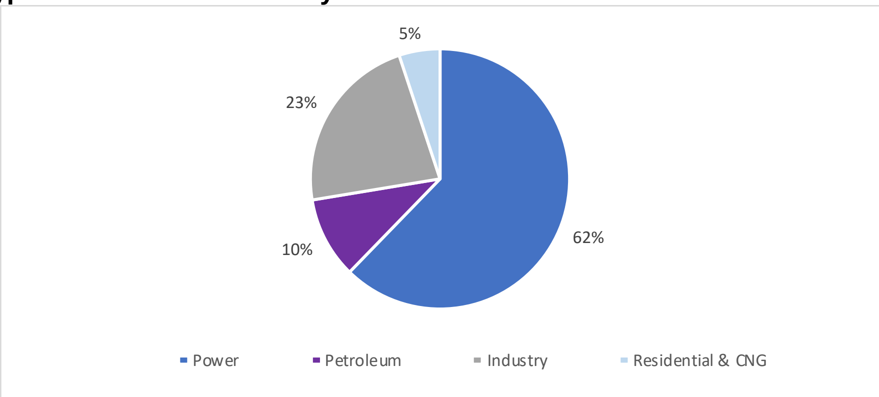
In 2013–2014, the Egyptian government initiated several hydrocarbon sector reform measures that enabled the relaunch of the country's upstream development activities (Ouki, 2018). In August 2015, Italy's Eni announced that it made a world class supergiant gas discovery at its Zohr prospect, in the deep waters of Egypt in the Shorouk Block, 160 km northeast of the city of Port Said.

The reform measures resulted in an increase of Egypt's gas reserves and fast-tracked new gas production, especially from the Zohr and West Nile Delta (WND) fields. The accelerated production from the Zohr field that started seven months ahead of schedule helped Egypt reach gas supply self-sufficiency. In 2018, Egypt's indigenous gas supplies were able again to meet the country's domestic gas needs and Egypt started slowly resuming its gas export activities. In September 2021, news reports indicated that Egypt stopped supplying gas to its largest LNG export complex at Idku (Stevenson, 2021c). But, it is not clear what this decision means. Is it a short-term gas supply adjustment since Egypt's other LNG complex at Damietta is reported to continue to receive feed gas supplies (Stevenson, 2021b) or the sign of a longer-term constrained gas supply?

In 2019, Egypt's total proven natural gas reserves were estimated at 2,221 billion cubic meters (bcm) or 78 trillion cubic feet (GECF, 2020). This reserve base remains limited relative to Egypt's growing domestic gas demand and the country's ambition to expand its gas exports, especially through its existing LNG plants at Idku near Alexandria and Damietta close to Port Said.

Egypt has the highest level of domestic gas use within the East Mediterranean area and the North Africa sub-region. In fact, Egypt ranks among the top five consumers of natural gas in the Middle East North Africa region. In 2018/2019, Egypt consumed about 62 bcm of gas or over 90 per cent of its marketed gas production. A rather fragile natural gas balance, where indigenous gas supply could at some stage be again insufficient to meet domestic gas demand. This would result in additional gas imports. The power sector is by far the largest gas user and accounts for over 60 per cent of Egypt's total use as presented in the figure below. Thus, meeting the natural gas needs of this critical sector of the Egyptian economy will continue to be a top priority for the government.

Figure 2: Egypt's Domestic Gas Use by sector – 2018–2019



Source: EGAS, 2020

Although it is not clear yet where potential supplies of low carbon hydrogen in Egypt would be produced and used, there is the possibility that some of Egypt's natural gas infrastructure could be considered for hydrogen transport in repurposed pipelines. Egypt has a well-established and extensive natural gas infrastructure with a total of 60,000 km of gas distribution pipelines and about 7,500 km of gas transmission pipelines.

However, one of the critical considerations with respect to the potential use of natural gas to produce blue hydrogen would depend on how Egypt's medium to long-term gas balance would evolve, especially under a relatively rapid gas demand growth situation and on Egypt's future strategy for the development of low carbon hydrogen. The different aspects that will drive this strategy and related policy considerations are covered in the sections that follow on the development of hydrogen in Egypt.

Hydrogen in Egypt

Current policies and plans

Within the framework of the 2015 Paris Agreement on climate change, Egypt is planning and implementing mitigation policies to reduce its level of greenhouse gas (GHG) emissions. This is outlined in Egypt's submitted nationally determined contribution (NDC) (UNFCCC, 2017) where mitigation actions are listed for each sector of the economy. For the energy sector, Egypt's largest GHG emitter, the focus is on a rapid increase of the share of renewable energy in the generation of electricity. In industry, another large source of GHG emissions in Egypt, industrial energy efficiency and pollution abatement projects are planned and/or being implemented.

Presently, Egypt is revising its "Integrated Sustainable Energy Strategy" and expanding it to 2040. In addition to a continued focus on the role of renewable energy in Egypt's energy mix, the development of low carbon hydrogen projects is also under consideration. A high-level committee of senior representatives from different ministries has been established to prepare a national hydrogen strategy for Egypt. The committee is to explore opportunities to produce low carbon hydrogen and available financing arrangements for these hydrogen projects.

Egypt is currently undertaking several actions towards the development of low carbon hydrogen initiatives and projects. It signed in January 2021, a letter of intention (LoI) with Germany's Siemens to produce green hydrogen in Egypt. This LoI was upgraded to a Memorandum of Understanding (MoU) signed in August 2021 with the Egyptian Electricity Holding Company (EEHC) "to jointly develop hydrogen-based industry in Egypt with export capability." This includes "the development of a pilot project, comprising 100 to 200 MW of electrolyzer capacity" (Siemens Energy, 2021).

In April 2021, Egypt signed an agreement with Belgium's DEME on the development of green hydrogen production in Egypt (Egypt Today, 2021). In July 2021, Italy's oil and gas major Eni signed an MoU with EEHC and EGAS "to assess the technical and commercial feasibility of projects for the production of hydrogen in the country" (Eni, 2021). More recently, in October 2021, an agreement was signed between the Egyptian\Emirati company Fertiglobe and Norway's renewable energy company Scatec for the joint development of a green hydrogen\green ammonia project to be sited at Ain Sokhna on the Red Sea coast (Stevenson, 2021a). Furthermore, in May 2021, Egypt received six offers from six different companies to setup green hydrogen projects in Egypt (Farag, 2021).

It is clear from this brief overview of Egypt's current policies and plans towards the reduction of its GHG emissions and the long-term transition to a greener economy that the government of Egypt is actively considering the development of a low carbon hydrogen economy focused on the production of green hydrogen. Thus, it is important to assess the situation of Egypt's present hydrogen market.

Existing hydrogen market

Data availability

Presently, all the hydrogen that is produced in Egypt is consumed domestically. However, there are no publicly available data on hydrogen production and consumption in Egypt. Therefore, an approximate high-level estimation of the existing market for hydrogen in Egypt has been carried out and is outlined in this subsection. The details of this estimation are presented in Appendix 1.

Main consuming industries

In Egypt, hydrogen is currently produced from natural gas using the steam methane reforming (SMR) process and is considered as grey hydrogen since the CO_2 emitted during the production process is not abated. Gas use for this hydrogen production is estimated at 13 per cent of Egypt's current domestic gas use. As presented in the previous section, Egypt has relatively large reserves of natural gas, but it has also a large and rapidly growing domestic gas demand that absorbs all or most of the country's marketed gas production.

In 2018–2019, the industry sector was the second-biggest gas user after the power sector with an annual consumption of about 14 Bcm or close to a quarter of Egypt's domestic gas use. The fertilizer industry alone accounted for about 46 per cent of the total industrial sector's consumption. It was followed by the iron and steel industry and the petroleum sector (refineries, petrochemical, methanol, and gas derivatives) as the second and third largest industrial consumers of gas in Egypt, respectively. All these natural gas-consuming industries are also the main consumers of hydrogen in Egypt.

Fertilizers

Hydrogen is used locally in the fertilizer industry to produce ammonia for the manufacturing of nitrogenous fertilizers. In 2019, Egypt produced 4.2 million tons of ammonia (US Geological Survey, 2020). Based on the assumption that hydrogen represents approximately 18 per cent of the ammonia weight, it can be derived that hydrogen consumption in the fertilizer industry in 2019 was approximately 756 thousand tons.[5]

[5] Calculations are explained in Appendix 1

Petrochemicals

Data from the Egyptian Petrochemical Holding Company (ECHEM)[6] show that in 2018, Egypt produced one million tons of methanol (Nouran, 2019). Half of the methanol production was sold in the local market while the rest was exported. The hydrogen content in methanol is 12.5 per cent by weight.

Therefore, for the 1 million tons of methanol produced in Egypt, the hydrogen consumption is estimated at 125 thousand tons.[7]

Steel

The steel industry is one of the main industries that consumes hydrogen extensively. Hydrogen is used for the reduction of iron ore in a process called Direct Reduction Iron (DRI). In Egypt, three steel companies have Direct Reduction Plants (DRPs); Ezz Steel, Beshay Steel, and Suez Steel company. Ezz Steel is the largest independent steel producer in North Africa and the Middle East and is the second-largest producer of DRI products in the world.[8] It has four DRPs with a total annual capacity of 5 million tons. Three of Ezz Steel's plants use Midrex technology, whilst HYL technology or zero reformer technology is used in its fourth plant.

Beshay Steel is the second-largest steel producer in Egypt with an annual capacity of 2 million tons.[9] It uses also the Midrex technology. The third-largest company, Suez Steel Company, has an annual production capacity of 1.95 million tons and uses zero reformer technology.[10] Thus, Egypt's direct reduction iron plants have a total annual production capacity of 8.95 million tons.

While Midrex technology has a reformer outside the shaft furnace, HYL technology carries out the reforming process inside the shaft furnace (N. Müller, 2018). 550 Nm^3 of hydrogen is required for every produced ton of DRI (Nm^3 H_2/tDRI) and an additional 250 Nm^3 H_2/tDRI is used as a heat source.[11] If both Midrex and HYL technologies consume the same amount of hydrogen, and each factory is operating at full capacity, the total hydrogen consumption in the steel industry would be 643.54 thousand tons annually.[12]

Refining

Globally, the refining industry is the largest consumer of hydrogen (IRENA, 2019). Nevertheless, it is very hard to estimate the amounts of hydrogen consumed by this industry. This is due to the combination of changing parameters that underly the refining process, such as sulfur content requirements and refinery configuration. Hydrogen is used in the hydrotreating process to catalytically stabilize petroleum products by removing unnecessary constituents and impurities from feedstock and products. Sulfur is one of the key constituents that needs to be removed due to its harmful effects on the human respiratory system and the environment. Other elements, such as nitrogen, oxygen, metals, and halides are also removed by hydrotreating. The sulfur removal by hydrotreating, or hydro-desulfurization, allows the recovery of sulfur and eliminate the need for on-purpose sulfur production (Praxair, 2017).

Egypt produces three main categories of crude oil blends: the Suez blend, the Belayim blend, and the Western Desert blend. Suez blend and Belayim blend are extracted from ageing offshore fields in the Gulf of Suez. Both are refined and consumed locally, with only a small volume being exported. Their sulfur contents expressed as a per centage by weight (per cent wt) are 1.65 per cent and 2.20 per cent wt, respectively. The Western Desert blend is produced from new oil fields in the Western Desert. These oil fields are currently the largest crude oil producers in Egypt and account for 56 per cent of the country's total production. Their sulfur content is 0.34 per cent wt (Fallon, 2018).

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[6] ECHEM has 12 per cent shareholding in Methanex's Egyptian subsidiary, the only producer of methanol in Egypt
[7] Calculations are explained in Appendix 1
[8] https://www.ezzsteel.com/about-ezz-steel/integration/direct-reduction-plants
[9] https://www.beshaysteel.com/categories/direct-reduced-iron/
[10] https://redseasteel.com/en/Plants/DRP
[11] https://www.midrex.com/tech-article/midrex-h2-ultimate-low-co2-ironmaking-and-its-place-in-the-new-hydrogen-economy/
[12] Calculations are shown in Appendix 1.

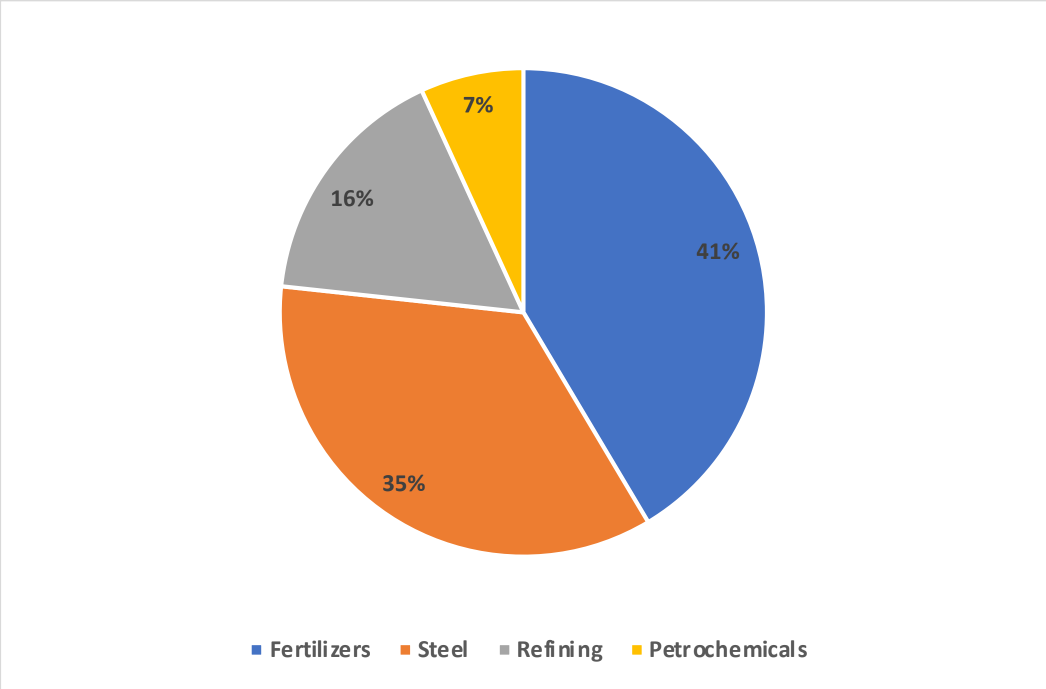
Table 6 in the appendices section shows the typical hydrogen consumption for different refining processes (Rabiei, 2012). In the case of Egypt, the value corresponding to high sulfur content was selected. Based on the data presented in this table, it is estimated that the amount of hydrogen used in Egyptian refineries is 1.085 per cent by weight of the refined crude oil volume.[13]

Egypt has a total refining capacity of 814,000 barrels per day (bpd). In 2019, its refineries' throughput was 559,000 bpd (OPEC, 2020). Therefore, it is estimated that around 300 thousand tons of hydrogen is consumed annually by Egypt's refining industry.

Hydrogen use summary

Based on the above-mentioned assumptions, Egypt's approximate total use of hydrogen is estimated at 1,824,540 tons in 2019.[14] Figure 3 and Table 2 show the sectoral breakdown of Egypt's estimated current hydrogen consumption.

Figure 3: Estimated sectoral breakdown of Egypt's current hydrogen use



Source: see Appendix 1

Table 2: Summary of Egypt's estimated hydrogen production\consumption (tons)

Ammonia Industry	756,000	Total
Steel Industry	643,540	1,824,540
Refineries Industry	300,000	
Methanol Industry	125,000	

Source: see Appendix 1

Replacing existing grey hydrogen use

Hydrogen is used extensively in Egypt's key industries. The potential introduction of low carbon hydrogen (blue or green hydrogen) is consequently focused on these industries that already consume grey hydrogen and are considered hard-to-abate sectors (where emissions are difficult to reduce).

[13] Calculations are explained in the appendix section.

[14] There are other sectors in Egypt that use hydrogen in the manufacturing process. For example, in the food industry, hydrogen is produced using electrolysis for unsaturated fat hydrogenation processes. However, hydrogen production in these other sectors is negligible compared to the above-discussed sectors.

Direct electricity-based solutions are not commercially viable and/or present technical drawbacks in these sectors.

Based on the total estimated consumption of about 1.825 million tons of grey hydrogen produced and consumed in Egypt, it can be derived that 16 million tons of CO_2 were emitted in the atmosphere. This represents 6 per cent of Egypt's present total CO_2 emissions that would be difficult to avoid or reduce. Therefore, low carbon hydrogen would have a crucial role in reducing emissions in Egypt's hard-to-abate industries. In the longer term, if feasible, low carbon hydrogen could also be introduced in other segments of the Egyptian economy.

Blue hydrogen is produced the same way as grey hydrogen, but with carbon capture and storage (CCS) or carbon capture, storage and utilization (CCUS) units to remove the CO_2 emitted during the process. It could initially play a role in the introduction of low carbon hydrogen in Egypt. However, due to Egypt's fragile natural gas balance and the fact that Egypt is actively developing a large renewable energy potential, this paper focuses on the potential long-term role of green hydrogen in Egypt's economy.

Green hydrogen is produced through different electrolysis technologies (mainly alkaline water electrolysis or proton exchange membrane or PEM electrolysis) using electricity produced from renewable sources of energy, such as solar and wind energy. It is estimated that about 61 MWh of renewable electricity is required to produce 1 ton of green hydrogen.[15] Therefore, it would require 110,585 GWh of renewable electricity to switch from the current production of grey hydrogen in Egypt to green hydrogen. The required installed renewable energy capacity to produce this level of renewable electricity supply would be 36 GW.[16] This would be a hugely challenging objective to reach given that Egypt's present total installed power capacity is just over 58 GW with the installed variable renewable energy capacity (excluding hydroelectricity) accounting for only about 4 per cent of this total.

In 2020, Egypt's installed renewable energy capacity was 5,982 MW, including hydroelectricity, and the total electricity generated was 24,870 GWh (NREA, 2021). This is the equivalent of only 22.5 per cent of the electricity that would be required to replace the current grey hydrogen production with green hydrogen. Thus, a substantial expansion of Egypt's renewable energy capacity would need to be developed with a dedicated capacity for green hydrogen production.

Decarbonisation challenges and opportunities

Adopting cleaner hydrogen production technologies, like blue or green hydrogen, to replace Egypt's grey hydrogen production is presently not economically viable at the current costs associated with the production of these categories of low carbon hydrogen. However, in addition to expected long-term cost reductions due to scaling up efforts, this could change as new international decarbonization measures, such as those envisaged by the European Union (EU), are implemented. According to the European Green Deal, the EU may impose a carbon border adjustment mechanism (CBAM) to avoid carbon leakages in case industrial production is transferred from the EU to other countries with less strict emission control measures or if EU products are replaced by more carbon-intensive imports (European Commission, 2019). The latter could be very relevant to the case of Egypt.

The EU is Egypt's biggest export and import partner. In recent years, trade between Egypt and the EU represented about 30 per cent of Egypt's total trade volume (European Commission, 2020). In 2019, total Egyptian exports to the EU were estimated at € 8.3 billion. Industrial products accounted for about 90 per cent of these exports. If CBAM measures are applied, Egyptian exports to Europe might be significantly affected by this carbon tax mechanism. Therefore, the introduction of low carbon hydrogen uses in hard-to-abate industries would prevent (or reduce) the imposition of this potentially onerous CBAM tax on imports of Egyptian products and would provide opportunities for Egypt to continue to develop and even expand its trade with the EU.

[15] Discussed in hydrogen production cost analysis section

[16] Assuming 50 per cent wind and 50 per cent PV and a combined capacity factor of 34.7 per cent according to NREA (NREA, 2021).

Potential additional hydrogen uses

Potential additional uses of low carbon hydrogen in Egypt, beyond replacement of existing grey hydrogen applications, could be considered.

New petrochemicals projects

In line with Egypt's 2020 – 2035 national petrochemicals plan, seven new petrochemical complexes are presently under development. These will utilize methanol, ethylene, and propylene as feedstocks to produce fifteen different products.[17] There are also several planned expansion projects that would require more feedstocks.[18] The production of additional volumes of feedstock, such as methanol, would require hydrogen. In the longer-term, this would potentially increase the industries' demand for low carbon hydrogen.

Electricity generation flexibility

The power sector in Egypt depends on large and centralized thermal power plants. The latest addition of the Siemens power plants is a good example of that.[19] The same capacity deployment approach has been applied to renewable energy power plants. As discussed earlier, large scale renewable energy power plants are being developed and several others are planned (NREA, 2021). This approach could present some electricity supply challenges for Egypt. To ensure the resilience of Egypt's power sector, electricity supply flexibility is needed to compensate for any operational failure in large renewable and non-renewable power plants.

This subsection briefly discusses the extent to which Egypt needs flexible electricity generation capacity and consequently comments on whether green hydrogen has a potential role to play in providing additional generation flexibility. To look at this critical aspect of electricity supply in Egypt, the case of the Benban solar energy project was considered. The Benban solar park is Egypt's largest renewable energy site and is one of the largest renewable energy complexes in the world. It is located in the Aswan governorate and consists of several power blocks with a total capacity of 1.465 GW. An interview with the general manager of operation & maintenance of Access Solar Egypt Operation and Maintenance Limited (ASEOML) - a subsidiary of Total Eren company - was conducted. ASEOML operates one of the Benban Park's power blocks.

Due to high temperatures that can reach 64 ^{0}C in the region where this solar park is sited, some of the power inverters in blocks near ASEOML's power unit stopped working and caused a sudden loss of energy. This unexpected loss can easily be compensated by contingency reserves. Furthermore, when the electricity generated by the Benban complex is larger than consumption, the extra energy produced must be curtailed or stored. This situation requires flexibility of the grid to accommodate and store this excess energy.

In fact, even with the current small share of renewable energy in Egypt's electricity mix, on several occasions, electricity generation has exceeded consumption in some areas. The potential electricity production of the Benban solar park has been curtailed because of the lack of storage options available. This problem could potentially be solved by cross-border electricity exports. But this requires timely availability of transmission infrastructure and an adequate commercial framework to quickly activate cross-border electricity supply transactions.

Consequently, the grid needs flexible resources such as energy storage to avoid renewable energy curtailment. Egypt is planning to develop a pumped hydro storage (PHS) project to be located near the Gulf of Suez where several wind power plant projects are sited. This PHS project will accommodate the variable renewable energy (VRE) that is produced from these wind power plants. However, it cannot provide flexibility for distant renewable energy plants, such as the Benban solar park, as the transmission lines will be overloaded. Therefore, other flexibility resources, such as the green hydrogen option, could be used subject to the availability of adequate hydrogen storage options (see section on "Challenges facing Egypt").

[17] More information and details can be found on ECHEM website http://echem-eg.com/project-under-development/

[18] idem

[19] https://new.siemens.com/eg/en/company/topic-areas/egypt-megaproject.html

Egypt is planning to achieve a target of 42 per cent renewable energy share in its total power capacity mix by 2035. With this ambitious growth of the share of variable renewable energy, the need for flexibility would be even more critical. Thus, in the long-term, as Egypt's VRE share in Egypt's total electricity output increases significantly, green hydrogen is one of the potential options that could be considered to address the issue of electricity supply flexibility. Hydrogen has several advantages, and it can be used on a small or large scale and for short-term and long-term storage.

But it should be stressed, that the use of hydrogen in the power sector to address flexibility issues remains a long-term option. Gas turbine and internal combustion engine manufacturers announced that their products can operate with 100 per cent hydrogen as a fuel. However, with a low-capacity factor that is expected when using hydrogen as a flexibility source, hydrogen is presently not the optimum choice.

Compressed Natural Gas (CNG) Vehicles

Egypt is planning to expand the use of natural gas in the transportation sector because of its environmental advantages compared with diesel and gasoline and a better efficiency (Habib and Mahmoud, 2020). Currently, there are in Egypt around 330,000 vehicles that are converted to run on CNG as a fuel. The Ministry of Petroleum announced that there is a plan to increase the number of converted vehicles by 263,000 by 2023 (El Ghandour, 2020).

In the long-term, green hydrogen could be considered as a cleaner alternative to CNG in the mobility sector. The transition from CNG to green hydrogen may take several approaches or options. The first approach would be to blend green hydrogen with the gas transported through the national gas grid that supplies CNG fueling stations. The second approach would be to repurpose the current CNG infrastructure to be compatible with green hydrogen. The last option would be to build a dedicated hydrogen refueling infrastructure.

The first option could be contemplated since several studies showed that hydrogen can be blended with natural gas at different percentage levels depending on each grid's situation and existing regulations (IEA, 2019). However, the CNG fuelling station itself would need to be modified to accept the fuel blend. A more powerful compressor would have to be installed to compensate for the lower energy density of hydrogen. In addition, CNG storage tanks need to be made of stainless steel and lined with polymer material to avoid embrittlement and permeation. Thus, the financial impact of the extra cost for the modification of the CNG fuelling station would have to be assessed to decide on the viability of such an option. The repurposing of CNG fuelling stations as the second alternative would be more problematic as it is expensive and therefore not financially attractive (Joan Ogdena, 2018). The last alternative of developing dedicated hydrogen refuelling infrastructure would be costly and is presently not feasible to consider.

Finally, the potential use of low carbon hydrogen beyond existing applications in Egypt's hard-to-abate industries remains very limited. Long-term options for the use of green hydrogen could be looked at when variable renewable energy sources of electricity reach a large share of Egypt's total electricity generation capacity. However, all the potential uses of low carbon hydrogen in existing or new applications will depend on its production costs. This critical aspect for the introduction of low carbon hydrogen in a country's economy is analyzed in the next section

Hydrogen production cost analysis

Scope of analysis

A high-level assessment has been carried out to estimate the production costs of grey and blue hydrogen for the case of Egypt. It is then followed by an economic analysis of the levelized cost of hydrogen (LCOH) for the potential production of green hydrogen in Egypt.

Two scenarios were considered for the green hydrogen cost estimation. Scenario 1 assumes an electricity supply price of US$ 72 per MWh representing Egypt's current price for industrial usage at medium voltage. Scenario 2 assumes a much more competitive electricity supply price of US$ 25 per MWh. This second scenario's electricity price reflects the current average price for the offtaker of renewable energy supplies in Egypt (assuming 50 per cent solar PV and 50 per cent wind energy mix).

This assumes that electricity could be produced and supplied on site, in the proximity of the hydrogen plant, at the above-mentioned average competitive price.

Grey hydrogen cost estimation

There are three main cost components to consider for the estimation of hydrogen production costs: capital expenditures (Capex), operating expenditures (Opex), and feedstock\fuel costs. This last component is the cost of natural gas for grey or blue hydrogen production using steam methane reforming or SMR technology. In this process, natural gas is used not only as a feedstock but also as a fuel. Natural gas cost is the most important cost component and could account for the largest share of total production costs, as shown in Figure 4 (IEA, 2019). Therefore, the volume of natural gas consumed and its price will essentially drive the cost of grey and blue hydrogen production. The typical efficiency for SMR technology ranges between 12.39 GJ/1000 Nm^3H_2 to 16.32 GJ/1000 Nm^3H_2 (130.652 MMBtu/tonH_2 to 172.096 MMBtu/tonH_2) (IEAGHG, 2017).

According to Egypt's fertilizer company MOPCO,[20] 165.89 MMBtu of natural gas is required (feedstock and fuel) to produce one ton of hydrogen and 6.5 tons of CO_2 is released during the production process[21] (MOPCO, 2021).

The natural gas price for gas supplied to petrochemical and fertilizer industries is set by prime ministerial decree and is presently fixed at US$ 4.5 per MMBtu. Using the above-mentioned required volume of natural gas used in the hydrogen production process and the set natural gas price, the cost of feedstock/fuel to produce grey hydrogen can be derived. In the case of Egypt, it is estimated at US$0.747 per kg H_2. Based on the IEA's assumption that Capex and Opex levels are the same across all regions (see Figure 4) and are estimated at US$ 0.500 per kg H_2 (US$ 0.340 per kg H_2 for Capex and US$ 0.160 per kg H_2 for Opex) (IEA, 2019), the estimated total production cost of grey hydrogen in Egypt would be US$1.247 per kg H_2.

From the above-mentioned gas use assumption, the total amount of consumed natural gas to produce grey hydrogen can be estimated also. Based on a total production of grey hydrogen estimated at 1,824,540 tons and that 165.89 MMBtu is required for every ton of hydrogen, the total volume of natural gas consumed can be derived using a natural gas calorific value of 1,041 Btu/scf (EGAS, 2019). Therefore, the total volume of natural gas consumed to produce grey hydrogen is 8.23 Bcm representing 13 per cent of Egypt's current total natural gas consumption.

Blue hydrogen cost estimation

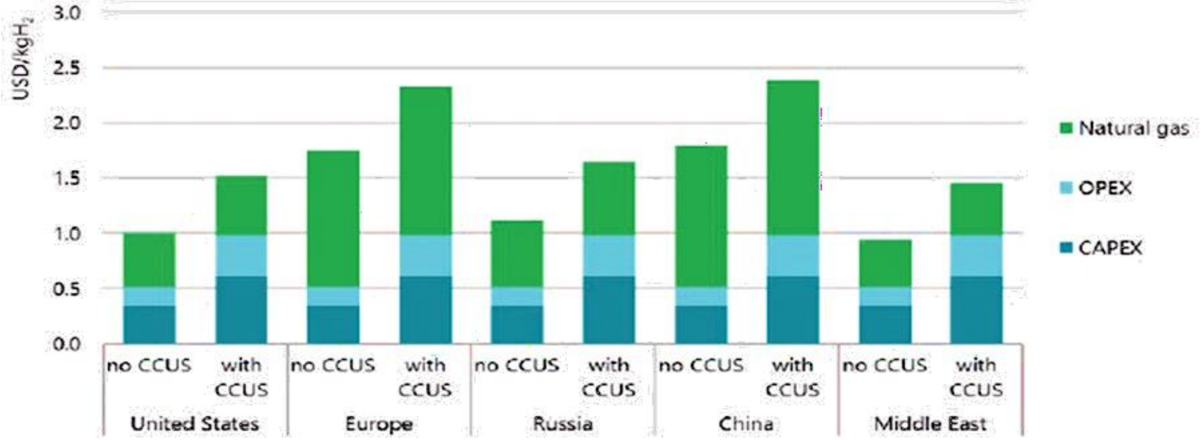
Blue hydrogen is produced the same way as grey hydrogen, but the CO_2 emitted from the production process is captured and stored or captured, stored and utilized through carbon capture and storage (CCS) or carbon capture, storage and utilization (CCUS) units. However, it is hard to estimate the expected cost of this low carbon hydrogen because of the difficulty of assessing the transportation and storage costs of CO_2. Furthermore, captured CO_2 can also be utilized and affect net hydrogen production costs.

Although it is complicated to calculate the blue hydrogen production cost, a high-level estimation could be made. According to the IEA, the use of CCUS increases the Capex cost component by 50 per cent, feedstock\fuel cost by 10 per cent, and it doubles the Opex cost component (IEA, 2019). Thus, using the previously estimated production cost for grey hydrogen of US$ 1.247 per kg H_2 and adding the CCUS cost increments for the Capex (+50 per cent or US$ 0.17 per kg H_2), Opex (+ 10 per cent or US$ 0.16 per kg H_2) and feedstock\fuel (x 2 or US$0.075 per kg) result in a high-level estimate of US$ 1.6517 per kg H_2 for blue hydrogen produced in Egypt.

[20] Misr Fertilizers Production Company (MOPCO) is the largest ammonia and urea producer in Egypt.

[21] 6.5 ton of CO_2/ton H_2 is considered low compared the estimated figure of IEA of 9 tons of CO_2/ton H_2. The explanation could be that part of CO_2 is captured for urea production in the factory.

Figure 4: Grey and blue hydrogen production costs



Notes: kgH_2 = kilogram of hydrogen; OPEX = operational expenditure. CAPEX in 2018: SMR without CCUS = USD 500–900 per kilowatt hydrogen (kW_{H2}), SMR with CCUS = USD 900–1 600/kW_{H2}, with ranges due to regional differences. Gas price = USD 3–11 per million British thermal units (MBtu) depending on the region. More information on the underlying assumptions is available at www.iea.org/hydrogen2019.

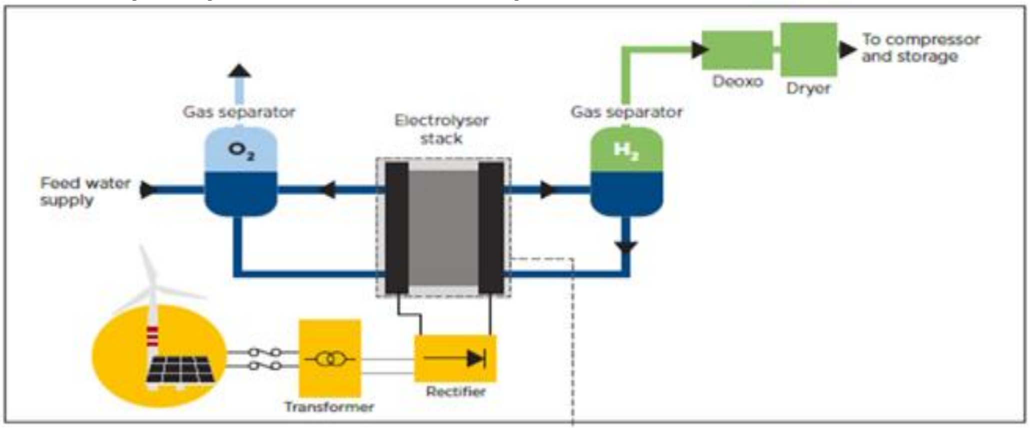
Source: IEA

Levelized cost of green hydrogen (LCOH)

Assumptions

Green hydrogen is produced by electrolysis that is powered by electricity supplied from renewable energy sources. The following two electrolysis technologies are predominantly used: Alkaline water electrolysis and Proton Exchange Membrane or PEM electrolysis. The analysis of the levelized cost of production of green hydrogen for each of these two technologies is presented in this subsection.

Figure 5: Electrolyzer system level as defined by IRENA



Source: IRENA

One of the key parameters that underly this production cost estimation is the system efficiency. There are different ways to estimate the efficiency of each technology resulting in diverse efficiency estimates.

This depends on how the system\plant boundaries are defined (Lettenmeier, 2019). IRENA defines the system boundary from the inlet of the electricity transformer to the inlet of the compressor that compresses hydrogen for storage purposes, as depicted in Figure 5. For this cost assessment, IRENA's boundary definition will be used for the system efficiency.

According to IRENA, PEM electrolyzer efficiency ranges from 50 to 83 kWh per kg H_2. Whilst for the alkaline water electrolyzer, the efficiency ranges from 50 to 78 kWh per kg H_2 (IRENA, 2020a). Based on the high heating value (HHV) of hydrogen, which is 39.4 kWh per kg, the resulting process efficiency ranges from 47.5 to 78.8 per cent for PEM electrolysis and from 50.5 to 78.8 per cent for alkaline water electrolysis.

Selecting a 65 per cent system efficiency for an alkaline electrolyzer, 60.61 kWh would be required to produce one kilogram of hydrogen. In the case of a PEM electrolyzer with a 70 per cent system efficiency, 56.28 kWh would be required to produce one kilogram of hydrogen.

Scenario Approach

An economic analysis of the cost of green hydrogen production was carried out for PEM and alkaline water electrolysis technologies to estimate the levelized cost of hydrogen (LCOH). This analysis has been conducted for two scenarios and using two capacity (utilization) factors; 30 per cent and 60 per cent.

Scenario 1 assumes a renewable electricity price of US$ 72 per MWh.[22] Therefore, the cost of electricity to produce green hydrogen under this first scenario would be US$ 4.364 per kg H_2 and US$ 4.052 per kg H_2 for alkaline and PEM electrolyzer technologies, respectively.

Scenario 2 is based on a very competitive renewable electricity price of US$ 25 per MWh.[23] This would result in an electricity cost to produce green hydrogen of US$ 1.515 per kg H_2 and US$ 1.407 per kg H_2 for alkaline and PEM technologies, respectively.

The above-mentioned cost figures for each scenario show the electricity cost only, which is by far the main production cost element, as depicted in Figures 6 and 7. The other cost elements included in the estimation of the LCOHs displayed in Tables 3 and 4 below, are incorporated in Figures 6 and 7 and their calculation explained in Appendix 2, where all the assumptions are listed.

The results of the LCOH analysis under the two scenarios are presented in the following tables:

Table 3: LCOH - Scenario 1
(current industrial electricity price fort medium voltage, US$ 72 per MWh)

Technology	**Capacity factor 30 per cent** (US$ per kgH_2)	**Capacity Factor 60 per cent** (US$ per kgH_2)
PEM	6.69	5.55
Alkaline Water	6.56	5.60

Source: see Appendix 2

Table 4: LCOH - Scenario 2
(current average renewable electricity price, US$ 25 per MWh)

Technology	**Capacity factor 30 per cent** (US$ per kgH_2)	**Capacity Factor 60 per cent** (US$ per kgH_2)
PEM	3.73	2.72
Alkaline Water	3.37	2.57

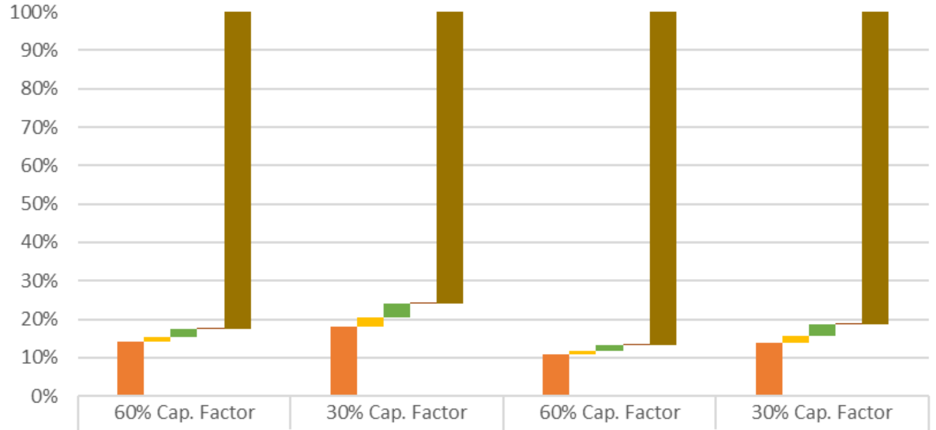
Source: see Appendix 2

As expected, Tables 3 and 4 show the significant impact of electricity prices on the LCOHs. Furthermore, the doubling of the capacity utilization factor clearly reduces the resulting LCOHs in all cases.

A graphical analysis of the different LCOH cost components and their shares of total costs is presented for the two scenarios in Figures 6 and 7. As shown in these figures, the largest cost component is electricity, followed by the Capex component.

[22] EgyptERA website, http://egyptera.org/ar/Tarrif2020.aspx
[23] Assuming that that 50 per cent will come from PV plants at 20 US$/MWh and 50 per cent from wind plants at 30 US$/MWh.

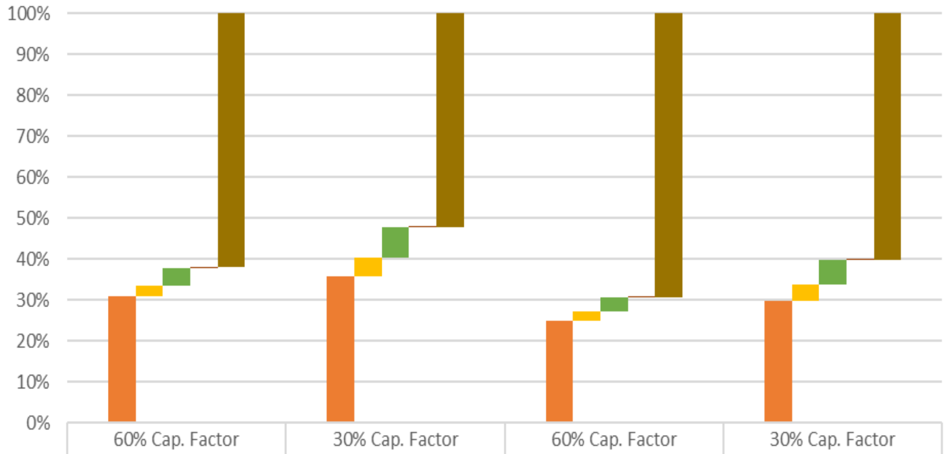
Figure 6: LCOH Cost component breakdown - Scenario 1



	PEM (USD/KgH2) 60% Cap. Factor	PEM (USD/KgH2) 30% Cap. Factor	Alkaline (USD/KgH2) 60% Cap. Factor	Alkaline (USD/KgH2) 30% Cap. Factor
Electricity	4.57	5.08	4.85	5.33
Water	0.004	0.004	0.004	0.004
Maintenance	0.11	0.24	0.08	0.18
Financing	0.07	0.16	0.05	0.12
Capex	0.79	1.21	0.60	0.92

Source: see Appendix 2

Figure 7: LCOH Cost component breakdown - Scenario 2



	PEM (USD/KgH2) 60% Cap. Factor	PEM (USD/KgH2) 30% Cap. Factor	Alkaline (USD/KgH2) 60% Cap. Factor	Alkaline (USD/KgH2) 30% Cap. Factor
Electricity	1.69	1.95	1.78	2.03
Water	0.004	0.004	0.004	0.004
Maintenance	0.12	0.27	0.09	0.20
Financing	0.08	0.18	0.06	0.13
Capex	0.84	1.33	0.64	1.00

Source: see Appendix 2

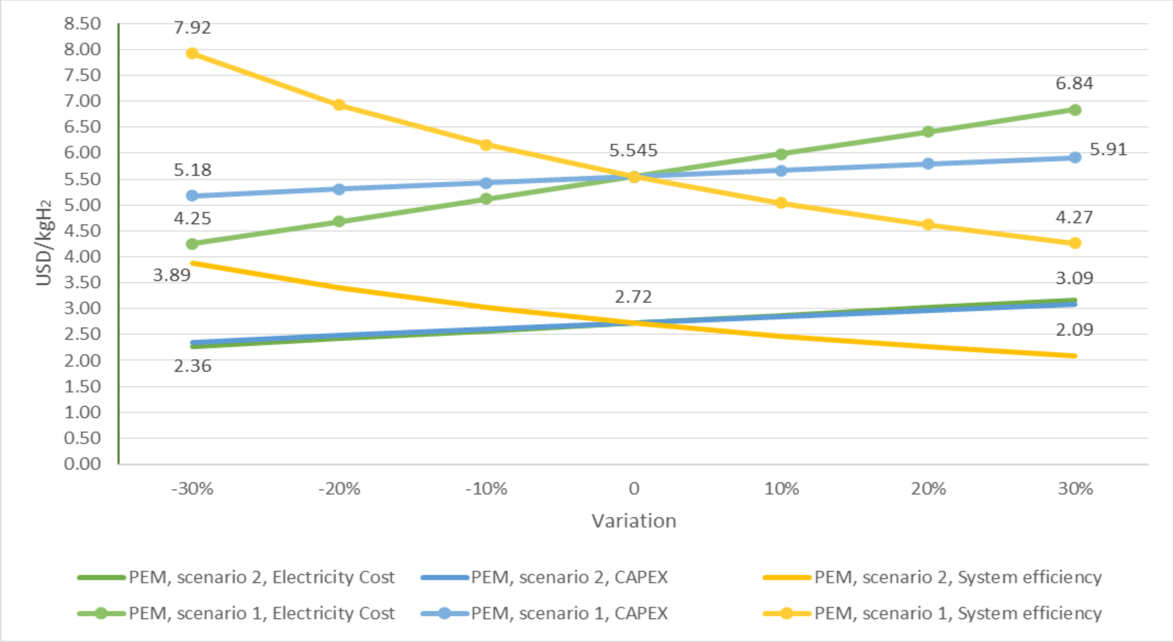
Sensitivity Analysis

To understand the impact of a wider range of changes in the key estimation parameters and assumptions, Figures 8 and 9 show the results of a sensitivity analysis for PEM and alkaline water technologies for both scenarios and based on a 60 per cent capacity factor reflecting the IEA's load factor assumption for future projects.

The analysis shows that changes in the system efficiency have the largest impact on the green hydrogen production costs. Improving the efficiency of the electrolyzer reduces greatly LCOHs.

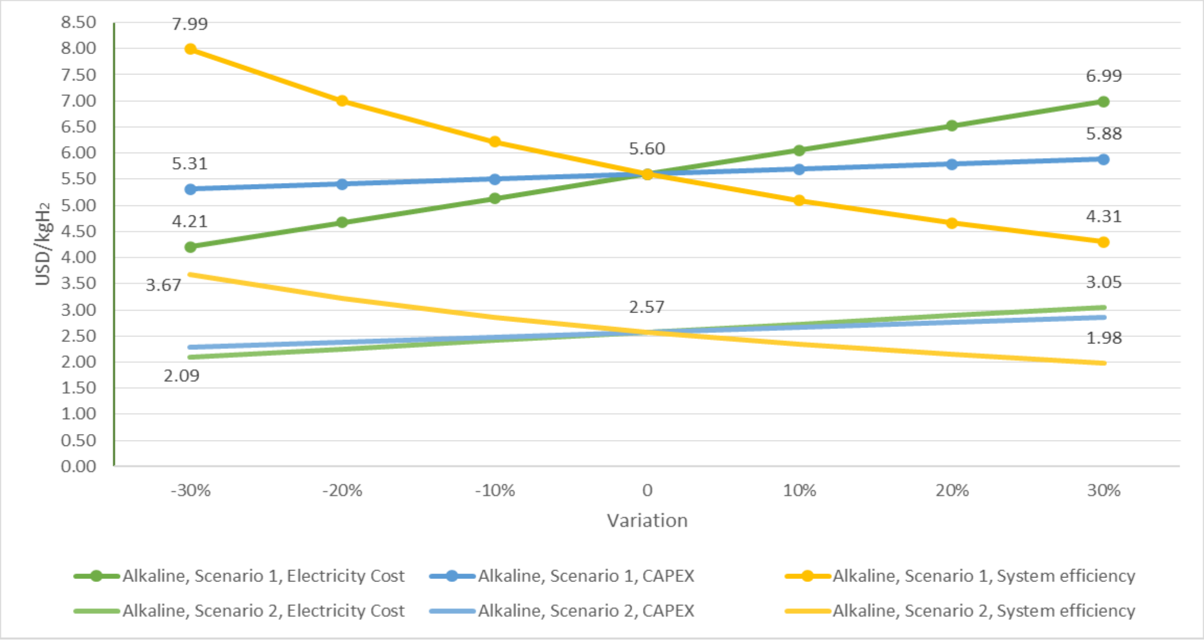
In Scenario 2, the impact of changes in the electricity cost and the Capex component is nearly similar. However, Under Scenario 1, the impact of the electricity cost on LCOHs is more pronounced than the impact of Capex changes.

Figure 8: Changes in LCOHs - PEM electrolyzer



Source: see Appendix 2

Figure 9: Changes in LCOHs - Alkaline water electrolyzer



Source: see Appendix 2

Summary

Based on the set of assumptions and two scenarios outlined above, the analysis of the hydrogen production costs of existing and potential new hydrogen supplies in Egypt shows the expected cost differences between grey hydrogen and low carbon hydrogen categories (blue and green hydrogen), as follows:

- Grey hydrogen — US$ 1.25 per kg of H_2
- Blue hydrogen — US$ 1.65 per kg of H_2
- Green hydrogen (Scenario 1) — US$ 5.55 – US$ 6.69 per kg of H_2
- Green hydrogen (Scenario 2) — US$ 2.57 – US$ 3.73 per kg of H_2

The analysis indicates that to achieve a competitive level of LCOH for green hydrogen, delivered supplies of renewable electricity to electrolyzers would have to be very cost competitive and well below the US$ 25 per MWh assumed under Scenario 2.

In the long term, when renewable energy capacity achieves a significantly higher share of Egypt's electricity generation mix and renewable energy projects of adequate size dedicated to the production of green hydrogen are implemented in a cost-competitive way, low and competitive green hydrogen LCOHs could become comparable with blue hydrogen production costs. But this is unlikely to happen for at least ten years.

The potential development of low carbon hydrogen supplies in Egypt will depend not only on the cost-competitiveness of these clean forms of hydrogen, but also on how several other inter-related challenges, as outlined in the following section, are addressed.

Challenges facing Egypt's hydrogen developments

The government of Egypt is actively working on the development of a low carbon hydrogen economy and there has been a lot of interest from international companies in green hydrogen initiatives and/or projects in Egypt. However, the implementation of low carbon hydrogen projects at the appropriate scale would take a long time to achieve. This is quite normal given the number of multi-faceted challenges Egypt – or any other country - would face in its low carbon hydrogen developments. In the case of Egypt, some challenges would impact these developments more than in other countries, as explained in the following subsections.

Renewable energy & electrolyzer scaling up

Focusing on green hydrogen developments, the issue of availability of dedicated renewable energy supplies to run electrolyzers is a main challenge. Egypt's present renewable energy targets are set to expand the clean electrification of the economy and to reduce carbon emissions produced by fossil-fuel-based thermal power plants. Diverting renewable energy supplies to produce green hydrogen would slow down this process. In fact, it would have an adverse effect by encouraging more fossil fuel consumption in the generation of electricity. This would also be inconsistent with the principle of "renewable energy additionality" that emphasizes that clean electricity should not be diverted from other productive uses to produce green hydrogen (IRENA, 2020b).

If Egypt opts to replace its existing production and consumption of grey hydrogen with green hydrogen to be potentially produced in Egypt, it would require the development of a huge renewable energy capacity. As presented in the previous section, it would require a total of 36 GW of dedicated renewable power capacity, which is equivalent to over 60 per cent of Egypt's current total electricity generation capacity. This would be a formidable challenge for Egypt.

Furthermore, this substantially large renewable energy capacity would be linked to the development in Egypt of a total electrolyzer capacity estimated at 21 GW. Globally, the maximum developed electrolyzer capacity available is a few hundred megawatts. Therefore, the scaling up to the gigawatt level would undoubtedly take time and require significant levels of investments.

Therefore, to address this scaling up challenge, the journey to a low carbon hydrogen economy in Egypt may initially require a gradual passage through blue hydrogen. A relatively cheaper low carbon hydrogen option to develop the market, but a challenging one as well.

CCS or CCUS

The production of blue hydrogen would require the addition of carbon capture and storage (CCS) or carbon capture, utilization, and storage (CCUS) facilities to capture, store and/or utilize CO_2 emissions from the hydrogen production process. Developing such facilities would present another category of challenges.

The CCS or CCUS technology is not mature yet and is costly to implement at large scale. It would certainly require government support, including direct financing, subsidies and/or regulatory incentives. Apart from the supporting regulatory framework, the other options would be very challenging for the Egyptian government to consider. Local or international private sector entities are still reluctant to commit to CCS or CCUS investments without strong government support.

According to the Global CCS Institute, there are 27 CCS commercial facilities in operation around the world, most of these facilities are in OECD countries (Global CCS Institute, 2021). Several of these CCS projects include the use of CO_2 in enhanced oil recovery (EOR) operations. In the case of Egypt, the CO_2 and alkali-surfactant-polymer injection methods could be applied. As the rate of production of several hydrocarbon fields in Egypt is declining, captured CO_2 could be used in EOR to enhance Egypt's hydrocarbon production from currently mature oil fields. A 2013 study surveyed 37 hydrocarbon reservoirs in Egypt to determine the most suitable reservoir for CO_2 injection. The results show that nearly all surveyed reservoirs are suitable for EOR operations using CO_2 and the expected incremental oil recovery increase is 10 percent of the original oil in place (Abu Ela, 2013).

In Egypt, the use of CCUS facilities to produce blue hydrogen can be applied in the ammonia industry, as the captured CO_2 can be used to produce urea at the same hydrogen production site with no transportation requirements. However, for refineries, methanol, and steel plants, long-distance CO_2 transportation would be required.

Hydrogen storage

In addition to the above-mentioned production challenges, once produced the low-carbon hydrogen volumes would need to be stored before consumption or transportation. This would be another level of challenges if commercially viable storage alternatives are not identified. Table 5 exhibits different hydrogen storage options and their associated costs (BloombergNEF, 2020).

For hydrogen storage at a gaseous state, the available options are salt caverns, depleted hydrocarbon fields and rock caverns, as presented in the table below. There are no data available about salt and rock caverns in Egypt. Depleted hydrocarbon fields could be an option for Egypt, which has several depleted hydrocarbon fields in the Nile Delta and Western Desert areas. However, this hydrogen storage option poses challenges. Storing hydrogen in depleted hydrocarbon fields can be problematic as the hydrogen can react with material left in the reservoir. Depleted hydrocarbon fields can contain sulphuric minerals or gas that could cause a release of a toxic gas, hydrogen-sulphide (H_2S).

Furthermore, the option of storing hydrogen in depleted hydrocarbon fields would be the most expensive option with a cost higher than the cost of blue hydrogen production and for the Benchmark LCOS a cost between about 50 and 75 per cent of the cost of green hydrogen production presented in the previous section (Scenario 2).

Storing low carbon hydrogen as green ammonia is currently the cheapest liquid state option. In the case of Egypt, it would not require the development of a completely new infrastructure for storing and transporting ammonia. Egypt already produces a relatively large volume of ammonia. It is Africa's biggest ammonia producer and has an established experience in ammonia production, storage, and transportation. But the option of storing green hydrogen through the production and storage of green ammonia would depend on Egypt's hydrogen development strategy. This would depend on whether the green hydrogen that could potentially be produced in Egypt could be fully utilized locally to replace grey hydrogen or if some of the green hydrogen and derived green products, such as green ammonia, would potentially be exported.

Table 5: Hydrogen storage options

	Gaseous state				Liquid state			Solid state
	Salt caverns	Depleted gas fields	Rock caverns	Pressurized containers	Liquid hydrogen	Ammonia	LOHCs	Metal hydrides
Main usage (volume and cycling)	Large volumes, months-weeks	Large volumes, seasonal	Medium volumes, months-weeks	Small volumes, daily	Small - medium volumes, days-weeks	Large volumes, months-weeks	Large volumes, months-weeks	Small volumes, days-weeks
Benchmark LCOS ($/kg)[1]	$0.23	$1.90	$0.71	$0.19	$4.57	$2.83	$4.50	Not evaluated
Possible future LCOS[1]	$0.11	$1.07	$0.23	$0.17	$0.95	$0.87	$1.86	Not evaluated
Geographical availability	Limited	Limited	Limited	Not limited	Not limited	Not limited	Not limited	Not limited

Source: BloombergNEF. Note: [1] Benchmark levelized cost of storage (LCOS) at the highest reasonable cycling rate (see detailed research for details). LOHC – liquid organic hydrogen carrier.

Hydrogen transportation

Most of the hydrogen presently produced globally is consumed locally close to its production site. Nevertheless, in the long-term, wider uses of low carbon hydrogen would require long distance transportation requirements. This would be another key challenge for the development of a hydrogen economy. Studies indicate that natural gas pipelines could be repurposed to accommodate 100 per cent hydrogen transportation or as a blend with natural gas. Egypt has an established and relatively large natural gas pipeline infrastructure and parts of this infrastructure could potentially be repurposed to transport hydrogen. But this would require a comprehensive audit of this gas infrastructure to assess whether part of it could be repurposed to transport hydrogen. Furthermore, pipeline capacity may not be available in potentially desired areas or regions. Therefore, a new dedicated hydrogen pipeline infrastructure would need to be developed. This would represent a bigger financial challenge than the pipeline repurposing option, especially for financially constrained economies such as Egypt's.

However, it is expected that future low carbon hydrogen production in Egypt would be mainly sited in industrial areas or parks, where the bulk of the hydrogen consumption would be located. This would reduce the impact of the hydrogen transportation constraint.

Water scarcity

The issue of water usage is often ignored or underestimated by analysts looking at green hydrogen projects, especially in regions other than the Middle East and North Africa (MENA) region. This is mainly because water consumption accounts for only a small share of the total cost of hydrogen production. But water scarcity in MENA countries has a critical social and economic impact well beyond the boundaries of a low carbon hydrogen project site.

Egypt is a water-stressed country that relies heavily on the river Nile as its main source of freshwater. Egypt receives less than 80 mm of rainfall per year (Dakkak, 2020) compared, for example, to 835 mm in Germany (Knoema, 2020). With a high rate of population growth and adverse climate change impacts, water supply availability is expected to become an ever-rising concern in Egypt in the coming years.

The electrolysis process requires approximately 9 liters of water to produce 1 kg of green hydrogen. Seawater cannot be used directly because it can lead to chlorine production and corrosive damage to the electrolyzer. However, seawater desalination could be a solution for Egypt to avoid the usage of freshwater. The cost of desalinated water would not considerably increase the cost of green hydrogen production. But seawater desalination would limit the locations where green hydrogen production plants could be sited as these plants would need to be developed in coastal areas. This could be a challenge for factories that are located far from seashores.

Furthermore, there is the issue of the energy intensity of desalination plants and their carbon footprint to consider, especially when international decarbonization measures become more stringent in the coming decades.

Legal and regulatory incentives

The formulation of a regulatory framework to support the development of a low carbon hydrogen economy in Egypt is likely to be a fundamental policy objective of the national energy strategy that is currently being prepared for Egypt. This would be in line with Egypt's long-term commitments to decarbonize its economy. The challenges would be to provide enough incentives that support this decarbonization.

Egypt is one of the few MENA countries that is engaged in the removal of domestic energy price subsidies, especially for natural gas and electricity. This has increased the production costs of industrial products and has even led some industries to switch from gas to more polluting fossil fuels. The introduction in Egypt of new regulatory measures such as a carbon pricing mechanism could increase further the costs of these manufactured goods. The argument of decreasing the carbon footprint of Egypt's internationally tradeable industrial products would be a valid one for the long-term, when international decarbonization measures become stringent and local industries are forced to reduce their production cost structures to remain competitive and maintain access to international markets. But in the medium term, implementing such decarbonization measures would be challenging for the Egyptian government. This is closely linked to the issue of financing low carbon hydrogen projects.

Financing

The current capital costs of electrolyzers range between US$500 and US$1,000 per kW for alkaline water electrolyzers and between US$ 700 and US$ 1,400 per kW for PEM electrolyzers (IRENA, 2020). These capital costs are a significant financing barrier for green hydrogen project developments. In the case of Egypt, the replacement of the existing grey hydrogen production with green hydrogen would require a total electrolyzer capacity of 21 GW, as indicated above. This would translate into a massive investment requirement ranging from US$11 billion to US$29 billion and these estimates do not include the costs of developing dedicated renewable energy capacity to supply electricity to the electrolyzers.

These capital expenditures would be phased during a long period of time, i.e., ten years or longer, and costs are expected to be reduced over time. Nevertheless, they would still be a challenging hurdle to overcome for the Egyptian economy, even if only half of Egypt's grey hydrogen production would be replaced with green hydrogen. Therefore, the financing of low carbon hydrogen projects would require the involvement of several partners, locally and internationally, combined with strong government support policies.

Egypt can consider the public-private partnership (PPP) funding model to overcome part of the capital cost barrier. Egypt had over 50 active PPP projects totaling US$10 billion (World Bank, 2017). PPP projects include a wide portfolio of projects in infrastructure, energy, and telecommunications. But this approach could address only a small portion of the large investments needed to develop green hydrogen capacity at scale.

An intermediary alternative to address this very difficult financing challenge Egypt would face in the production of green hydrogen would be to focus initially on the addition of CCS or CCUS facilities to its existing grey hydrogen production units to produce blue hydrogen and build up a market for low carbon hydrogen. As a matter of fact, Egypt's fertilizer company MOPCO is planning to install a carbon capture plant and use the captured carbon for urea production. It should be noted, however, that although blue hydrogen is a cheaper low carbon hydrogen alternative compared to green hydrogen, the large-scale development of CCS and CCUS units remains a challenge. But, in the longer term, the stringent implementation of international decarbonization measures, such as the EU's proposed CBAM, is likely to accelerate the need for CCS or CCUS applications, especially in hydrocarbon producing economies.

Conclusions

Egypt has one of the largest economies in the Middle East and North Africa (MENA) region and several of its key industries (fertilizers, steel, refining and petrochemicals) are among the region's largest consumers of unabated grey hydrogen.

Egypt's current total consumption of grey hydrogen, which is produced locally, results in large levels of CO_2 emissions. Therefore, the Egyptian government in its efforts to decarbonize the economy is planning to develop low carbon hydrogen alternatives and has set up an inter-ministerial committee to prepare a national hydrogen strategy for Egypt. Several international companies have also expressed interest in undertaking low carbon hydrogen initiatives or projects in Egypt. These are mainly focused on the production of green hydrogen to leverage Egypt's large renewable energy potential in both solar and wind energy. At present, Egypt has the MENA's largest installed capacity of renewable energy with relatively competitive generation costs.

Egypt offers a large domestic market for potential low carbon hydrogen (blue or green hydrogen) supplies. Thus, the replacement of Egypt's current use of grey hydrogen with low carbon hydrogen, especially in hard-to-abate sectors would be a highly desirable decarbonization target. However, this option is presently not commercially attractive, as the cost of green hydrogen production is much higher than grey or blue hydrogen production costs. Also, the high cost of developing large scaled up CCS or CCUS units required to produce blue hydrogen remains a main barrier.

Like many countries aspiring to develop a low carbon hydrogen economy and more specifically a large green hydrogen capacity, Egypt faces a series of challenges. Among the key barriers that constrain this decarbonization objective are the interlinked issues of availability of large and dedicated capacity of renewable sources of energy; timely scaling up of electrolyzer capacity; and the multi-billion-dollar financing of the whole green hydrogen supply chain, from the dedicated sources of renewable energy to the hydrogen storage and transportation segments.

The need for a supportive legal and regulatory framework is a key prerequisite for the development of a low carbon hydrogen economy. However, its formulation and successful implementation depends on the type of economies considered. In the case of economies that are financially constrained, such as Egypt's, the potential financial impact of such regulatory measures (e.g., development of a national carbon pricing mechanism) on local industries could in the short to medium-term delay or undermine their implementation. This situation could arise if decarbonization regulations lead to increases in the costs of goods the Egyptian industries produce. Furthermore, the likely call from these industries for government subsidies to compensate for the cost increases would be very difficult for the Egyptian government to address. Nevertheless, in the long run, the requirement to significantly reduce the carbon footprint of manufactured products would force unavoidable changes. Egyptian industries, such as those where emissions are hard-to-abate, would have to decarbonize their products to maintain access to key international export markets.

Egypt's green hydrogen development prospects would depend on Egypt achieving a significantly higher share of renewable energy in the country's electricity generation mix with cost-competitive renewable energy supplies fully dedicated to the production of green hydrogen.

The blue hydrogen option could be considered as a transition alternative to grey hydrogen. But the funding barrier posed by the CCS or CCUS issue would need to be addressed quite rapidly. It is also important to note that Egypt's current production of unabated grey hydrogen accounts for a non-negligible share of the country's domestic gas consumption. Furthermore, blue hydrogen production would require additional volumes of natural gas for the CCS or CCUS units. Although this incremental gas volume requirement is relatively small, it could become critical in periods of tight gas supply. If Egypt's natural gas balance faces again supply challenges, it is not only a potential blue hydrogen production that would be affected, but it is also the country's existing natural gas-based grey hydrogen production that would be constrained.

We introduced this paper by indicating that Egypt is one of the first countries in the MENA region to produce green hydrogen. But because of cost considerations this green hydrogen experience was stopped two years ago. Can Egypt resume its production of clean hydrogen and develop a large scaled up low carbon hydrogen economy?

Obviously, several fundamental changes have taken place in Egypt and the world since that first green hydrogen initiative was launched more than sixty years ago. Especially transformations in the way energy resources are and will be produced and consumed within the context of the on-going energy transition towards a decarbonized world.

Egypt remains an important candidate for the potential development of green hydrogen production and use. However, this potential would need time to materialize. Addressing the above-mentioned challenges would be a long-term process that goes beyond 2030. Yet, Egypt's preparation for this low carbon hydrogen journey should start in earnest and be based on realistic, clear, and achievable milestones.

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Appendices

Appendix 1: Estimation of local hydrogen consumption

A. Estimation of hydrogen use in ammonia industry

Ammonia (NH_3) is composed of nitrogen and hydrogen. The molecular mass of Nitrogen is 14, and the molecular mass of Hydrogen is 1.

The total molecular mass of ammonia: 14+(1×3) = 17

The weight percentage of hydrogen in ammonia is: 3 ÷ 17 = 17.6 per cent. ≈ 18 per cent

Egypt's ammonia production in 2019 was 4,200,000 tons

Hydrogen supply required to produce the above amount: 18 per cent × 4,200,000 = <u>756,000 tons</u>

B. Estimation of hydrogen use in methanol industry

Methanol is composed of hydrogen, oxygen, and carbon (CH_3OH). The molecular mass of oxygen is 16, the molecular mass of carbon is 12, and the molecular mass of hydrogen is 1.

The total molecular mass of ammonia: 12+16+ 1×4 = 32

The weight percentage of hydrogen in methanol is: 4 ÷ 32 = 12.5 per cent

Egypt's methanol production in 2018 was 1,000,000 tons

Hydrogen supply required to produce the above amount: 12.5 per cent × 1,000,000 = <u>125,000 tons</u>

C. Estimation of hydrogen use in steel industry

800 Nm^3 of hydrogen is required for each DRI ton produced in steel industry. The hydrogen density at normal condition is 0.08988 kg/m^3.

800 × 0.08988 = 71.9 kg H_2 is required for each DRI ton produced in steel industry.

Egypt's total annual production capacity using DRI is 8,950,000 tons.

The required amount of hydrogen for the above production is

8,950,000 × 71.9 = 643,540,800 kgH_2 ≈ <u>643,540 tons</u>

D. Estimation of hydrogen use in oil refining industry

Table 6: Typical hydrogen per centage used in the refinery process

Process		Per cent Wt. of Crude	Selected value
Hydrotreating	Straight run naphtha	0.01	0.01
	Cracked naphtha	0.05 - 0.1	0.075 (Average)
Hydro-desulfurization	Low sulfur gas-oil to 0.05per cent S	0.04	NA
	High sulfur gas-oil above 0.05per cent S	0.05	0.05
	Cycle oils hydrogenation	0.3	0.3
	Hydrocracking vacuum gas-oil	0.5 - 0.8	0.65 (Average)
Total			1.085

Source: Rabiei, 2012

Based on the above table, the required amount of hydrogen in the refining industry after adding the selected value is 1.085 per cent by weight of the refined crude oil volume. The throughput of Egypt's refineries in 2019 was 559,000 barrel/day.

Egypt's refinery annual throughput is 559,000×365 = 204,035,000 barrel/year.

One metric ton equal to 7.33 barrels.

204,035,000÷7.33 = 27,835,607 tons.

Hydrogen production required to produce the above amount:

1.085 per cent × 27,835,607 = 302,016 ≈ 300,000 tons (rounded)

E. Total estimated amount of hydrogen use

- Ammonia: 756,000
- Methanol: 125,000
- Steel: 643,540
- Refining: 300,000

1,824,540 tons

Appendix 2: Assumptions of economic analysis

Table 7: Assumptions for green hydrogen production cost for PEM electrolyzer

Name	Assumption	Notes/Reference
System size (MW)	100	
Electricity price (USD/MWh)	Scenario 1: 72 Scenario 2: 25	Scenario 1, (EgyptERA, 2021) Scenario 2: see text
System Capex (USD/kW)	900	IEA's Capex estimate of 900 US$/kW
System lifetime (years)	20	Based on IRENA's lifetime assumption of 20 years
System Efficiency (per cent)	70 per cent	Average between IRENA's estimate of 78.8 per cent and the IEA's 64 per cent efficiency
Stack lifetime (hours)	70,000	Assumption between IEA's estimate of 95,000 hours and IRENA's estimated range of 50,000-80,000 hours
Stack cost /System Cost (per cent)	45 per cent	(IRENA, 2020)
Capacity Utilization factor (per cent)	30 per cent 60 per cent	30 per cent: assuming the same capacity factor as PV power plants in Egypt[24] 60 per cent: reflecting the IEA's assumption
Water consumption (liter/kgH2)	9	(IEA, 2019)
Cost of water (USD/kg)	0.000375	(Egyptian Desalination Research Center, 2021)
efficiency decline (per cent / year)	1.50 per cent	Estimated from different sources
Maintenance (per cent of Capex)	1.00 per cent	IEA's Opex estimate is 1.5 per cent. However, for Egypt's case 1 per cent is sufficient.
debt financing per cent	50 per cent	Assumed a 50 per cent\50 per cent debt\equity
Debt interest rate per cent	5.25 per cent	Egyptian green bonds yield
Debt period (Years)	5	
Discount factor	6 per cent	Based on IRENA's WACC assumption

Source: see Notes\Reference

[24] Actual Capacity factor for wind power plant in Egypt is 39 per cent (3,415 full load hours), 30.4 per cent for PV power plants (2,659 full load hours). These figures are based on information included in the NREA 2020 Annual Report (NREA, 2020).

Table 8: Assumptions for green hydrogen production cost for Alkaline electrolyzer

Name	Assumption	Notes/Reference
System size (MW)	100	
Electricity price (USD/MWh)	Scenario 1: 72 Scenario 2: 25	Scenario 1, (EgyptERA, 2021) Scenario 2: see text
System Capex (USD/kW)	650	
System lifetime (years)	20	Based on IRENA's lifetime assumption of 20 years
System Efficiency (per cent)	65 per cent	IRENA's estimated system efficiency ranges between 50.5 and 78.8 per cent
Stack lifetime (hours)	60,000	IEA's estimated range is 60,000-90,000 hours. IRENA's estimate is 60,000 hours
Stack cost /System Cost (per cent)	45 per cent	(IRENA, 2020)
System Utilization factor (per cent)	30 per cent 60 per cent	30 per cent: assuming the same capacity factor as PV power plants in Egypt 60 per cent: reflecting the IEA's assumption
Water consumption (liter/kgH2)	9	(IEA, 2019)
Cost of water (USD/kg)	0.000375	(Egyptian Desalination Research Center, 2021)
efficiency decline (per cent / year)	1.50 per cent	Estimated from different sources
Maintenance (per cent of Capex)	1.00 per cent	IEA's Opex estimate is 1.5 per cent. However, for Egypt's case 1 per cent is sufficient.
debt financing per cent	50 per cent	Assumed a 50 per cent\50 per cent debt\equity
Debt interest rate per cent	5.25 per cent	Egyptian green bonds yield
Debt period (Years)	5	
Discount factor	6 per cent	Based on IRENA's WACC assumption

Source: see Notes\Reference