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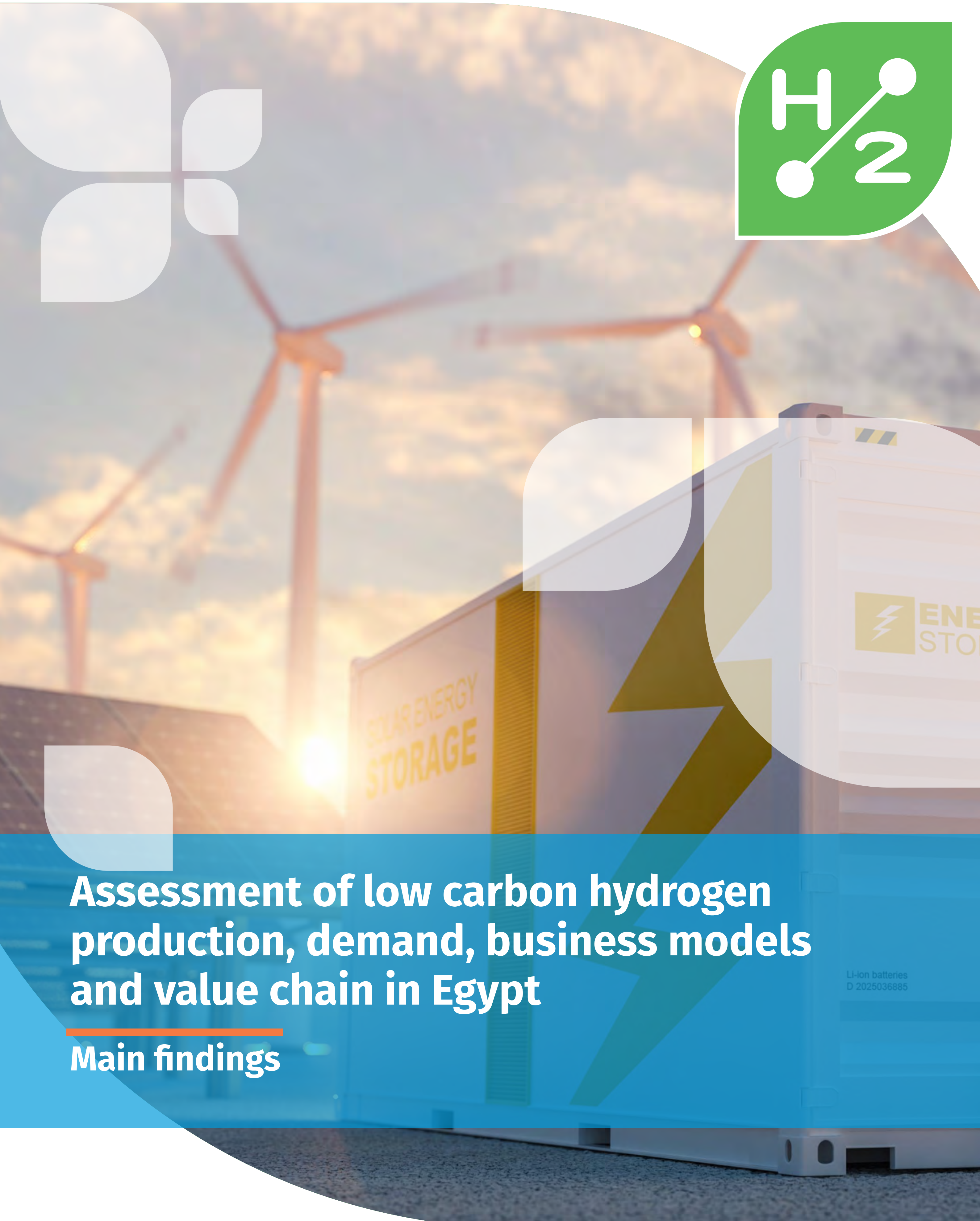
GLOBAL PROGRAMME
HYDROGEN IN INDUSTRY



Assessment of low carbon hydrogen production, demand, business models and value chain in Egypt

Main findings

About

This document presents a summary of project activities carried out in Egypt. The project aimed to assess the potential for a low-carbon hydrogen market in Egypt, strengthen the country's readiness for market development and promote its usage for industry decarbonization. The project supports public and private institutions in Egypt with knowledge of low carbon hydrogen production potential, current and future demand scenarios, development of business models and creation of value chains.

The project is part of the UNIDO's Global Programme for Hydrogen in Industry. Through its Programme, UNIDO aims to influence and guide the development of market polices, standards, skills, financing instruments, innovation and coordination between key stakeholders that play an essential role in the development of a just and sustainable hydrogen economy. Promoting tangible projects to accelerate the local uptake of green hydrogen in industries of developing countries and transition economies is a key element of the Programme.

The project in Egypt was led by UNIDO, together with two strategic partners: Italian University, Politecnico di Milano and the Environmental Compliance Office - Federation of Egyptian Industries.

The overall goal of the project was to:

- Assess the competitiveness of hydrogen pathways in Egypt;
- Investigate the suitability of hydrogen production routes (including derivatives), considering both domestic and international markets;
- Analyse the regulatory framework;
- Conduct a survey of possible business models for hydrogen;
- Analyse the potential for greenhouse gas (GHG) emission reductions.

Partners

The United Nations Industrial Development Organization is the specialized agency of the United Nations that promotes industrial inclusive and sustainable development for poverty reduction, inclusive globalization and environmental sustainability in Member States. UNIDO's mandate is fully recognized in SDG-9, "Build resilient infrastructure, promote inclusive, sustainable industrialization and foster innovation".

Politecnico di Milano is a world-renowned scientific-technological university, which trains engineers, architects and industrial designers. Since its foundation in 1863, Politecnico di Milano has gained an in-depth experience in teaching and researching activities, as well as developing a long-lasting relationship with the business & productive world by means of experimental research and technology transfer. According to the QS Global World Rankings 2022, the University ranks 1st among Italian universities and among the first 20 globally.

Fondazione Politecnico di Milano is a university foundation and research organization, established in 2003 by its public state university of reference Politecnico di Milano. The Hydrogen Joint Research Partnership is a research platform that promotes innovative studies and research in production of clean hydrogen (green and low carbon) and associated transport solutions.

Environmental Compliance Office & Sustainable Development (ECO SD): As part of the Federation of Egyptian Industries (FEI), which represents over 104,000 industrial enterprises (90% private sector); more than 2 million workers and 18% of the national economy, ECO SD was established within FEI in 2001. ECO SD provides consultancy services to the industrial sector with the aim of promoting Sustainable Development and to support the industry with Circular Economy methods, practices and technologies. ECO SD is a member of the National Green Hydrogen Committee, which highlights the importance of hydrogen technology for different industrial sectors and discusses potential opportunities for green hydrogen in Egypt, as well as establishment of a national council for hydrogen in Egypt.

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Environmental Compliance Office and Sustainable Development

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Key indicators

The following tables summarize the project's key indicators that can guide the reader.

INDICATOR AND UNIT	#
Population (million, 2022)	102.87
GDP (billion $, 2020/2021)	443
Industry contribution to GDP (%, 2022)	16.8
Egyptian energy sector (% of GDP)	13.1
Renewable energy % in grid (%, 2016)	~10
Renewable energy target 2035 (%)	42
Natural gas reserves (tcf, 2021)	63
Annual natural gas production (tcf, 2019)	2.3
Annual natural gas consumption (tcf, 2019)	2.1
Industry use of national gas (%)	23
Fertilizer industry use of national gas (%)	10
Ammonia use of national gas (%)	8
Desalinated water production (M m^3/day)	1.4
Ammonia production (M tons/year, 2020)	~ 5.5
Avg. electricity prices, renewable ($/MWh)	20-25
Green ammonia CO_2 cost (USD/ton)	75
Methanol production (M tons/year, 2018)	1
Steel production (M tons/year)	8.95
Refineries H2 use (KTPA, 2019)	300
CO_2 storage for 2500 years (Gt)	86-600
Signed MoUs for H_2 (#, 12/2022)	19
Egypt national GHG (Mt, 2016)	219
Industry national GHG (Mt, % of total)	61 (28)
H_2 national GHG (Mt, % of total)	17 (6)
Ammonia national GHG (Mt, % of total)	10 (3)
Blue H_2 carbon intensity (kg CO_2/kg H_2)	0.8 – 4.4
Green H_2 carbon intensity (kg CO_2/kg H_2)	< 3

Levelized costs of hydrogen and derivatives (pre-feasibility level) are presented in the table below:

INDICATOR AND UNIT	#
Ammonia cost (USD/ton) 2030	620-740
Ammonia cost (USD/ton) 2050	540-660
Hydrogen cost (USD/kg) 2030	1.8-2.3
Hydrogen cost (USD/ton) 2050	1.3-2.1
Methanol cost (USD/ton) 2030	711-820
Methanol cost (USD/ton) 2050	620-750

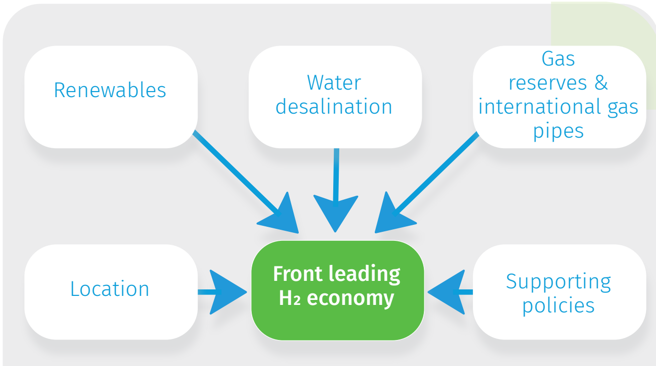
Context and background

Source

The country's location

Egypt is located in the North-Eastern part of Africa, bordered by the Mediterranean Sea to the North and the Red Sea to the East. With an area of over 1 million Km², Egypt is at the crossroads between Europe, the Middle East, Asia and Africa. It is a major shipping hub, with easy access to the Mediterranean and Red Sea (Europe – Asia shipping trade route) via Suez Canal.

Its unique geographic location, and being the second largest signatory of multilateral trade agreements in the world, Egypt connects investors with both established and emerging markets. The country is well positioned to play a functional role in the hydrogen economy. The country's location coupled with the abundance of renewable energy resources, natural gas infrastructure and associated skills, is combined with sectoral enabling policies, strategies for water desalination and industrial know-how in hydrogen and ammonia production and related exports. All the above places Egypt **in a unique position to develop a front-leading hydrogen economy, both for Egypt and potential neighboring markets**.



Favorable factors

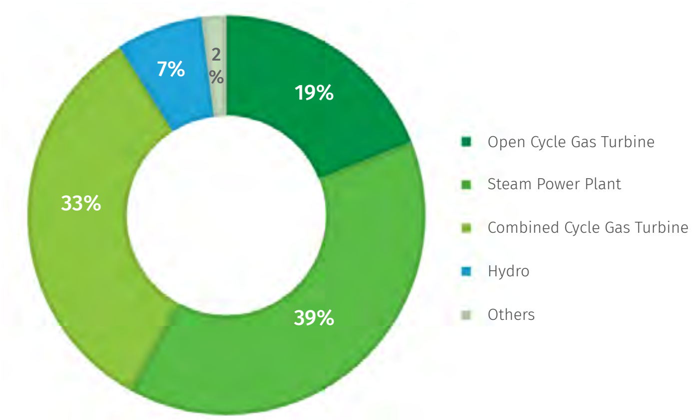
Natural energy resources

The Egyptian energy sector is a key driver for the socio-economic development of Egypt, representing around **13.1% of current GDP** and thus making economic growth in the country contingent upon the security and stability of energy supply. Since 2007, Egypt has experienced an energy supply deficit due to the rapid increase in energy consumption and the depletion of domestic oil and gas resources, shifting its position from a net hydrocarbon exporter to a net importer for the last three decades. This has brought a set of challenges to the energy sector, including electricity shortages. In response, the Government of Egypt has taken bold steps to adopt an energy diversification strategy with increased development of renewable energy and implementation of energy efficiency measures, including rehabilitation and maintenance programs in the power sector.

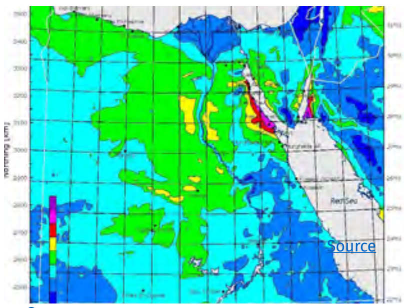
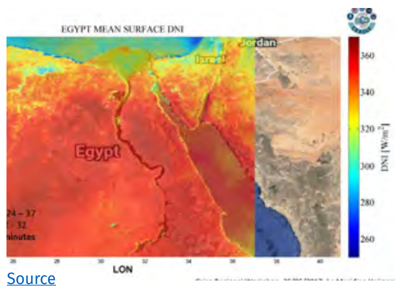
Egypt put forth the **new Electricity Law in 2015** that began a gradual market liberalization in the country's power sector. Building on that and with the goal of scaling up renewable energy projects, the government has taken several steps to reform the legislative environment for the energy sector and increase the investment incentives for renewable energy projects.

Egypt has an abundance of renewable energy resources with high deployment potential, including hydropower, wind, solar and biomass which position it as a prime location for renewable energy projects. According to **the Egyptian energy strategy 2035**, Egypt is working on increasing the supply of electricity generated from renewable sources to **42% by 2035**, with wind providing 14%, hydropower 1.98 %, photovoltaic (PV) 21.3 %, concentrating solar power 5.52 %, and conventional energy sources 57.33% by 2035. This plan is currently being revised and waiting the approval of the supreme council for energy to reflect 33 % of energy generated from renewable energy by 2025, 48 % by 2030, 55 % by 2035, and 61 % by 2040, with a capacity increase from 3.2 GW in 2020 to 54 GW by 2035) as well as improvements in energy efficiency.

The total installed electricity generation capacity in the year 2015/16 amounted to 38 857 megawatts (EEHC, 2016a), as per the breakdown (left). The private sector contributed 2048 MW through the BOOT scheme for thermal electricity generation capacity. Peak load was recorded at 29.2GW in 2015/16 (EEHC, 2016a). Regarding power consumption, the total final energy consumption reached 80.0 Mtoe in 2019/2020 and is set to reach 114.0 Mtoe in 2034/2035. Out of the total installed electricity, renewable energies (hydropower, wind and solar) accounted for almost 10%.



Renewables energy breakdown

TYPE	DESCRIPTION	INSTALLED	LAND	MAP-ATLAS
HYDROPOWER	With an average growth 1.2% from 2011 to 2021. The main hydro resource in Egypt is the river Nile, with the highest potential in Aswan where several power stations are located generating 13,545 GWh annually	2,832 MW	Aswan	 Source
WIND ENERGY	High stable wind speeds, along with the availability of large uninhabited desert areas, particularly in the Gulf of Suez area. Wind speeds between 8-10 m/s at a height of 100 m	542.3 MW in Zaafarana; 580 MW in Gabel El-Zeit; 262.5 MW in Ras Ghareb	Gulf of Suez East Nile West Nile	 Source
SOLAR ENERGY	2900 - 3200 hours of sunshine annually. Total radiation intensity of 2000 - 3200 kWh/m²/year. New capacities (2021) include 140 MW Koraimat, 1465 MW (PV) in Benban region (private sector), 26 MW (PV) in Kom-Ombo	4,466 GWh, 479 GWh from Kuraimat solar plant Isolated and reserve units - 217.2 MW	West Nile Bemban Kom-Ombo East Nile	 Source

Natural gas resources

Regarding natural gas, Egypt is the third-largest natural gas producer in Africa. According to the Oil & Gas Journal, Egypt holds **63 trillion cubic feet** of proved natural gas reserves as of January 2021. In terms of annual production, in 2019, Egypt was producing about 2.3 Tcf of dry natural gas with **a consumption of 2.1 Tcf (59 BCM)**. That means, Egypt absorbs all or most of the country's gas annual production. However, recent discoveries of natural gas have been achieved:

- Nooros discovery in Nile Delta, North Alexandria.
- West Nile Delta in Mediterranean Sea.
- Zohr discovery, considered the largest natural gas discovery in Mediterranean Sea and one of the largest natural gas discoveries worldwide.

Egypt also has a wide **knowledge and experience on the liquefied natural gas sector**. Egypt currently has two LNG export facilities, the Italian-Egyptian Gas Company (EGAS) LNG facility and the Egyptian LNG facility (ELNG).

- EGAS LNG is a single LNG train located in Damietta on the Mediterranean coast. Since the start of commercial operations in 2004, Egypt underutilized EGAS LNG, leading to the plant's closure in December 2012 as a result of growing domestic energy demands. The plant restarted LNG exports in February 2021 after Eni, Naturgy, and the government of Egypt reached an agreement to restart the plant.
- The Egyptian LNG facility (ELNG) is located at Idku and has 2 LNG trains. Production began in May 2005, but like the SEGAS the facility experienced a temporary shut-in in 2015 as a result of high domestic demand for natural gas and insufficient feedstock for the facility to export.

All the above natural energy resources play an essential role in the coverage of energy demand in Egypt. The Ministry of Petroleum and Mineral Resources has adopted an integrated plan to develop and upgrade the gas grid infrastructure, in particular gas pipelines which are the most vital link in the gas supply chain. The Egyptian Gas Grid is continuously upgraded and sustained which made it the largest and longest in Africa and the Middle East (exceeding 66.5 thousand km with capacity about 250 million cubic meter/day by end of June 2020). Furthermore, these pipelines could be assessed for future use for green hydrogen transportation.

Water for GH_2 production

Egypt is a water-stressed country that relies heavily on **the Nile River** as its main source of freshwater (underground water, rain and floods and water recycle). Water demand is estimated around 80 bcm annually. However,

Source

Nile River only supplies around 59.52 bcm which entails a shortage gap of around 20 bcm annually.

The Ministry of Irrigation and Water Resources in Egypt announced a strategy in the last years to resolve all water-related problems that Egypt faces until 2050. According to the strategy, Egypt is expected to produce significant amounts of desalinated sea water. Currently Egypt produce produces **1.4 million m³/day of desalinated water** and plans to increase the number and size of desalination plants to produce **8.8 million m³/day**. In 2022, Egypt started to work on the readiness for desalination of industrial areas such as Suez Canal Zone and Ain El-Sokhna to incentivize green hydrogen investments.

Water from desalination is expected to be the main source of water for green hydrogen production which will require only 20% of the planned desalinated sea water production in Egypt. Green hydrogen is produced by splitting water by electrolysis and it requires a significant quantity of high-purity water (nominal consumption is 9 kgH2O/kgH2). In Egypt, the main source of water would be seawater; the water purification process is around 50% efficient, so it requires twice the volume of seawater per unit of high-purity water.

Climate commitments

Egypt ratified its Paris agreement in the year 2017, submitting its first INDC in 2016 and the biennial report in 2018. Despite the strong communication effort, the NDC does not report any emission reduction targets as compared to 1990 or 2005 levels, but only to projected BAU levels. Egypt also released its Egypt Vision 2030 report in February 2016 which aims to reduce the greenhouse gas emissions from the energy sector by 10% compared to it 'current value' [of 2016]. Also, a strong emphasis is placed on building energy self-sufficiency, and incorporating more renewable energy in its electricity mix.

Last, the NDC recognizes the importance to decarbonize the industrial sector by replacing feedstock with green hydrogen to produce green ammonia and transition towards low carbon fertilizer production.

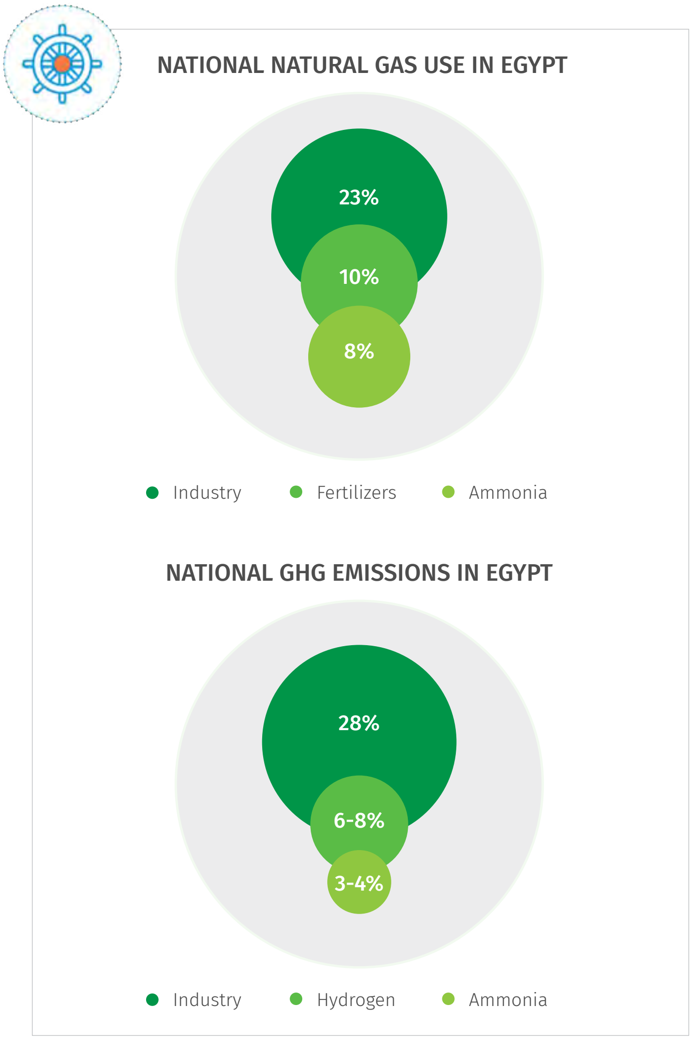
Hydrogen in Egypt

Hydrogen use

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. The Egyptian industrial sector is considered one of the key sectors contributing to national GDP with an average contribution of 16.8% in 2021/2022, reaching 70.9 billion Egyptian pounds in 2020/2021 and export value of 25.9 billion dollars in 2021/2022.

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. In 2018–2019, the industrial 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 (23%)** (displayed in the figure on the right). The fertilizer industry alone accounted for about 10% of the total gas use or 46% of the total industrial sector's consumption, followed by petroleum sector (refineries, petrochemical, methanol, and gas derivatives – 9.1 % or 5.4 BCM) and iron and steel industry (3% or 2.1 BCM).

According to Worldmeter, in 2016, **fossil CO_2 emissions was 219,377,350 tons or 219 Mt**, a 5% higher than the year before. In this context, the Egyptian industrial sector is the third-largest contributor to GHG emissions from energy use (28%), which requires industries to adopt measures to reduce its related GHG emissions. The hydrogen industry alone is responsible of **6%** of the total emissions, making ammonia production in the country 3-4% of the total (displayed in the figure on the right).



Fertilizers

Hydrogen is used in the fertilizer industry to produce ammonia for the manufacturing of nitrogenous fertilizers. Egypt is considered the 9th largest ammonia exporter with estimated amount of 160 KTPA. The average **ammonia production reached 5.5 million tons in 2020**. As the weight percentage of hydrogen in ammonia is 18 %, accordingly the hydrogen supply required for the production of 5.5 million tons of ammonia, is almost **one million tons**.

From the total consumption of natural gas in nitrogen fertilizers production, about 80% (**8%** of total gas use in the country) is used in fertilizers as feedstock for H_2 and 20 % of the natural gas acts as the energy source that is required for the fixation of atmospheric nitrogen to manufacture ammonia.

Demand for ammonia is expected to increase from new sectors, predominantly for shipping with ammonia (along with methanol). The cost of natural gas-based ammonia production is in the range of **USD 110-340 per ton of ammonia**, depending on natural gas prices. This requires of a CO_2 cost of USD 75 per ton of CO_2 compared to cleaner options such as green ammonia.

Green ammonia can be 2-3 times more expensive, USD 720 to USD 1400 per ton. However, it is estimated that green hydrogen technology can cover the gap by 2030 as the cost of electrolysers and renewable electricity declines. According to our results estimates, green ammonia may be produced (by 2030) at a competitive cost between **USD620 per ton and USD740 per ton** in areas with good renewable resources.

Petrochemicals

Data from the Egyptian Petrochemical Holding Company (ECHEM) show that in 2018 Egypt produced **one million tons of methanol.** Half of the methanol production was sold in the local market while the rest was exported.

Steel industry

Steel industry is one of the main industries that consumes hydrogen extensively in Egypt. 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):

1. 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. It has four DRPs with a total annual capacity of 5 million tons.
2. Beshay Steel is the 2nd largest steel producer in Egypt with an annual capacity of 2 million tons.
3. The third-largest company, Suez Steel Company, has an annual production capacity of 1.95 million tons and uses zero reformer technology.

Egypt's direct reduction iron plants have a total annual production capacity of **8.95 million tons**. According to the United Nations COMTRADE database on international trade, the exports of iron and steel were US$1.72 Billion in 2021.

Refining

Egypt produces three main categories of crude oil blends:

» Suez blend;

» Belayim blend; and

» Western Desert blend.

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% of the country's total production (sulphur content 0.34 %).

The average hydrogen consumption by Egyptian refiners is around **300 KTPA in 2019**.

Low Carbon Hydrogen

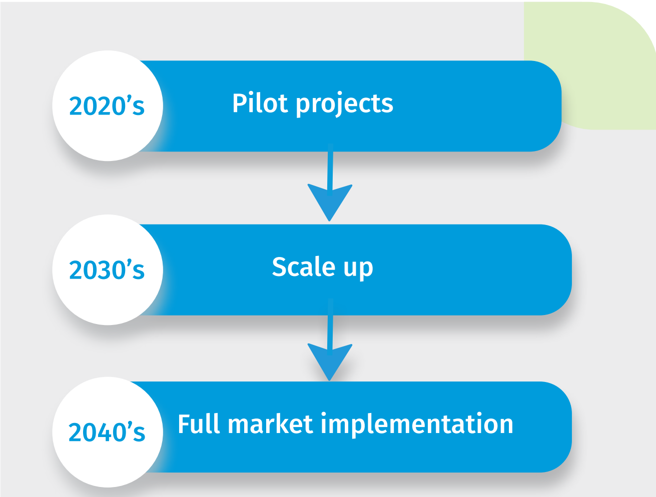
Green hydrogen is produced by using renewable energy to power the electrolysis of water. Converting current hydrogen uses to green hydrogen can significantly reduce carbon emissions from the Egyptian industrial sector, which is currently responsible for about one-quarter of all energy-related CO_2 emissions in the following industries – iron & steel, chemicals and petrochemicals, and cement. In fact, 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.

Blue hydrogen is when natural gas is split into hydrogen and CO_2, either by Steam Methane Reforming (SMR) or Auto Thermal Reforming (ATR), but CO_2 is captured and then stored through a Capture Usage and Storage process (CCS). It is generally reported to be cheaper than green hydrogen, at least in the short-medium term.

Hydrogen (regardless of its production pathways) that meets a greenhouse gas emission reduction threshold of 70%, is also known as **low-carbon hydrogen**, which this project explores. In this line, Egypt has the potential of producing blue hydrogen that can comply with this criterion, as long as the CCS technology is effective and in place.

The competitiveness of blue and green hydrogen is dependent on the natural gas price, and the potential of large-scale CO_2 storage. The existence of potential CO_2 sinks in depleted natural gas reservoirs located close to oil and gas production operations and industrial sites with significant concentrations of CO_2 emissions offer an opportunity for the development of CCS hubs in the country. According to Rystad Energy, the total CO_2 storage potential in Egypt ranges **between 85 and 600 Gt of CO_2 approximately 2,500 years of storage**, when compared to the 2018 emissions from industry, electricity and heat producers in Egypt. The blue hydrogen option could be considered as a transition alternative to green hydrogen, while gradually phasing out grey hydrogen. But the funding barrier posed by CCS or CCUS technologies would need to be addressed quite rapidly.

In November 2022 at the COP27, the Egyptian Government announced **the national low carbon hydrogen strategic framework**, in which Egypt will play a leading role in the supply of hydrogen and derivatives for the development of a low-carbon hydrogen economy. Egypt will be competitive to become a hub for low-carbon hydrogen, **targeting up to 8% (10 MTPA) of the tradable market by 2040**. It is estimated that current hydrogen demand in Egypt is about 2% of the global annual demand.



National low carbon hydrogen strategic framework

Today, Egypt is currently undertaking several actions towards the development of low-carbon hydrogen initiatives and projects. At the time of this project (November – December 2022), there were around **19 signed memoranda of understanding**. 18 projects will be located in SCZone and only 1 will be located in East Port-Said on the Mediterranean Sea. The MoUs are between a number of government agencies, represented by the New and Renewable Energy Authority (NREA), the General Authority for the Suez Canal Economic Zone (SCZone), the Egyptian Electricity Transmission and Distribution Company (EETC), and the Egypt Sovereign Fund, and leading global companies and in the production of renewable energy.

Contracts for around 6 MOUs have been signed during COP27, and 100% from the new projects aim to export as a phase one; while phase 2 starting in 2030 will aim to consume green hydrogen at local scale and pushing the Egyptian industries for its use.

Green/Low-Carbon Hydrogen Clusters

Industrial clusters have a big role to play in the clean energy transition. Having clusters of industries – specifically heavy users of fossil fuels - such as cement, steel, fertilizers, and petrochemicals, physically in the same location can create and facilitate internal markets for hydrogen, avoiding investing in long-distance infrastructure. An additional competitive advantage would be the proximity of potential clusters to renewable water sources, and marine ports.

Launched in 2015, **the Suez Canal Economic Zone** (SCZone) is considered one of the top potential clusters for green hydrogen especially with the existence of currently ammonia production facilities.

The SCZone, extending over 461 km², comprises **four industrial parks and six ports**. The ports are placed from North to South along the canal. Each hub within the zone is dedicated to selected industrial sectors. For instance, East Port Said is being developed as a hub for pharmaceuticals and automotive parts, while Ain Sokhna specializes in heavy industries, including petrochemicals, ceramics, and fertilizers. Qantara caters to SMEs and agribusinesses, while East Ismailia also called "Technology Valley" for its emphasis on high tech, research, and renewable energy. The six ports in the SCZone are undergoing major development:

Mediterranean coast:

- **East Port Said**, a top-performing port worldwide, it includes manufacturing activities such as automotive engineering, construction, textiles, mainly operated by shipping giant Maersk.
- **West Port Said** handles 8.7 million tons of multipurpose cargo annually.
- **Al Arish Port**, a 2000 m² site that specializes in dry bulk, general cargo and agricultural products.

Red Sea:

- **Al-Tor Port** is focused on services for oil & gas companies.
- **Ajdabiya Port** handles dry bulk, liquid bulk, and cargo.
- **El Sokhna Port** which is Egypt's main gateway to the Gulf Cooperation Council (GCC), East Africa and Asia with an area of 23 Km².

Additionally, the SCZone is located in close proximity to both offshore wind farms of El Zaafarana and to the 1220 km² allocated land by the national renewable energy authority "NREA" for wind generation in the Gulf of Suez area. However, no land has been allocated for solar energy so far in this area as conditions are not optimal for green hydrogen production, also shown by our LCOH calculations.

The work concluded **ammonia is the most prominent sector for green hydrogen use** and an optimal potential carrier for hydrogen especially for cross ocean movement. A prioritization criterion for green hydrogen clusters would focus on competitive factors similar to the already exiting in the SCZone;

- Close proximity of marine ports,
- Close proximity to off takers,
- Close proximity to renewable energy
- Land availability,
- Close proximity to sea water desalination facilities.

Accordingly, establishing green/low-carbon hydrogen clusters where off takers and commercial marine ports are in relative adjacent proximity, is essential to lower transportation costs and associated the infrastructure and at the same time minimize safety concerns. As a result of the studies and assessments conducted, the following **fertilizer companies and locations** have been identified as potential green/low-carbon hydrogen off-takers:

Off-takers:
Alexfert Fertilizer / Abu Qeir Fertilizer
Location: Alexandria

Off-taker:
MOPCO company
Location: Damietta

Off-taker:
SEMADCO
Location: Al Adbeya port

Off-taker:
East Port Said industrial zone
Location: East Port Said

Potential green/low-carbon H_2 off-takers

Hydrogen / Ammonia industrial value chain

Identifying the green hydrogen value chain in Egypt requires mapping the potential technical cooperation interventions to support and upgrade the value chain. The green hydrogen value chain can be considered a combination of green electricity production, hydrogen production, hydrogen distribution and storage as well as the various hydrogen applications in mobility, industry, heat supply or base chemistry.

The mapping lists entities and sectors that could potentially support the green hydrogen value chain in the following areas/dimensions: **a) Policy and Governance b) Technical Support c) Capacity Building d) Private sector interventions and finally e) Financial support**

The supply chain pathway for green hydrogen production comprises two main steps, renewable power production, and then use of this power to drive the electrolysis process that produces hydrogen.

It is expected that the electrolyzer might use multiple sources of renewable power (multiple solar and wind

Entities and sectors supporting the green hydrogen value chain in Egypt assets), assuming that power would be transmitted via the existing electricity grid. This is achieved by a local connection between renewable power production and the grid, and a second connection between the grid and the electrolyzer at the destination point for power transfer. In Egypt, there is little hydrogen infrastructure for transporting hydrogen over significant distances at scale, as all bulk hydrogen demand is met via dedicated captive hydrogen production plants (i.e., produced and used on the same site for industries such as ammonia production and petroleum refining). Concerning storage of hydrogen, the vast majority of hydrogen used today is also captive, but as the production of hydrogen increases in Egypt, there will be a greater need for storage.

Local manufacturing potential in green electricity production especially solar and wind energy is also important to support local value chains. The solar sector in Egypt has already a significant number of active players. Egypt has key strengths for solar industrial development due to low cost of labour and low cost of energy for industrial consumers as well as availability of materials, such as glass, steel, and stainless steel. For wind energy, NREA encourages local manufacturing of turbines and other components based on technology transfer or joint ventures. In this line, Egypt has previous experience that has been gained with small-scale manufacturing of wind turbine components as well as repairs and rewinding of generators have been carried out by local companies.

Another important element to support the value chain is **the related occupations and jobs** in green hydrogen that will require qualified individuals with engineering capabilities and/or specialized expertise. Thus, the green hydrogen ecosystem will require new skills and changes for the existing training programs to address the specific requirements and technologies of the hydrogen sector.

Competitivity of hydrogen production routes, including derivatives

The focus is put on green hydrogen production from wind and solar, with blue hydrogen also being considered. The main parameter of interest is **the levelized cost of hydrogen** (LCOH), which represents the total cost of hydrogen production over the lifespan of the plant investment, hence, the minimum sale price. This is estimated for each hydrogen production pathway. **Transformation into ammonia and methanol** is also considered.

Two approaches are considered:

1. For hydrogen production via electrolysis, the LCOH is evaluated through numerical elaboration;

Here, the source of electricity may be:

- a dedicated renewable power generation plant (i.e., wind or solar photovoltaic, PV), with or without electrical storage systems, or;
- the power grid.

Because of that, using one option or the other implies **different costs and different indirect CO_2 emissions**.

The capital expenditure (CAPEX) is related to the renewable plant(s), the battery energy storage system (if any), and the electrolyzer (EC). Investment costs are expected to decrease over the next decades. Besides fixed O&M costs, the operational expenditure (OPEX) is basically null for dedicated renewable power generation (since there is no cost related to consumption of sources), while it depends upon electricity market prices in the case of grid-based operation.

The overall LCOH is estimated through an ad-hoc spreadsheet simulation framework, which allows considering different **combinations of wind and solar generation for a selected location and different sizing options for the electrolyzer**. For derivatives, additional CAPEX and OPEX for the technologies that transform H_2 to ammonia or methanol are considered.

2. While for blue hydrogen (i.e., hydrogen from natural gas via steam reforming equipped with CO_2 capture and sequestration), the LCOH is mainly derived from process simulation studies available in the scientific literature.

The calculation of LCOH requires various types of input data, such as economic and technical data, and the availability of renewable sources in different locations:

- **Economic data** consists of capital investment, operating, and maintenance costs of technologies;
- While **technical data** includes performances of technologies, efficiencies, and their lifetime.

The investment costs and fixed O&M are expected to decrease over time due to the economies of scale, and three scenarios are considered to estimate LCOH, which are **today's cost, 2030, and 2050**, respectively. The costs and efficiencies of photovoltaic, wind, battery, electrolyzer, carbon capture and storage technologies are taken from various sources such as NREL and IEA. Electricity prices are assumed to be 20-25 $/MWh which is an average electricity price for renewables.

The availability of renewable energy sources is obtained in **ten selected geographic locations** through the renewables.ninja webtool, which returns the hourly electricity generation profiles.

The team conducted a parametric analysis to calculate the Levelized Cost of Hydrogen (LCOH). Different configurations were investigated, by combining:

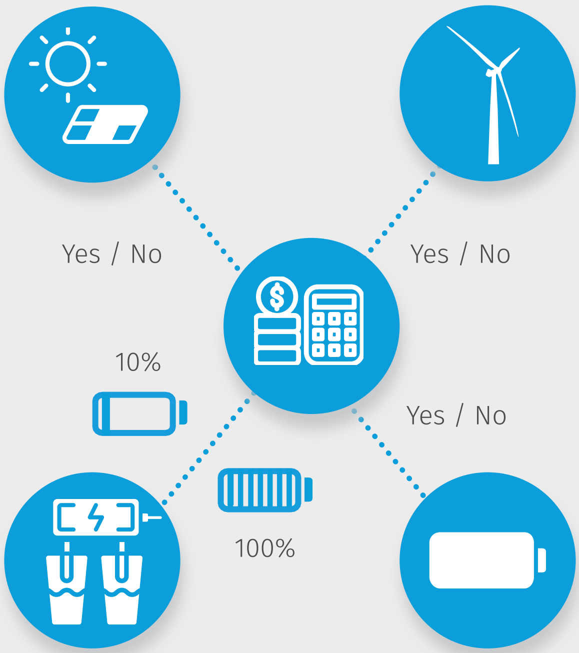
Power generation sources: only wind or only solar

Load operation: variable with minimum load required 10% or constant at full load

Varying the size of electrolyzer: from 10% to 100% of the renewable plant capacity

Availability of the battery: **yes or not**

Configurations for a LCOH calculation

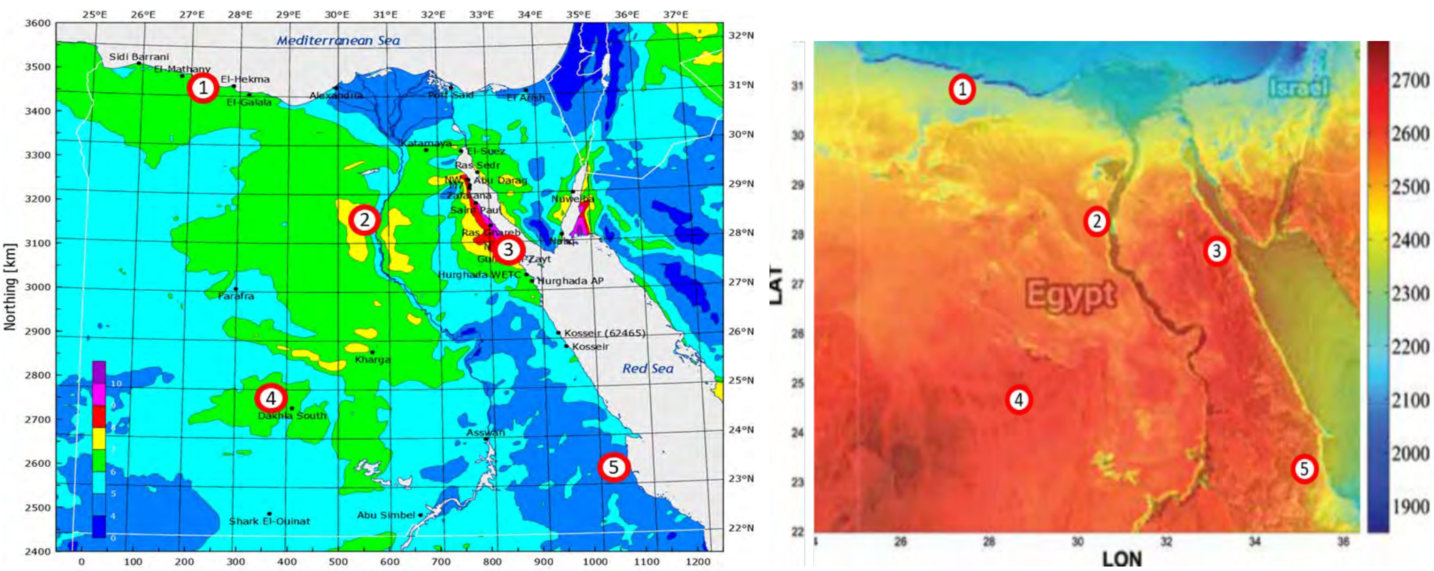


Parametric analysis

10 locations were analysed:

(i) Five locations (picture below, 1 to 5) were chosen based on the renewable potential and their proximity to the sea (for water availability) or to the existing power grid (assuming the renewable power generation may be located away from the hydrogen production);

(ii) Five more locations (Alexandria Port, Al Adbeya Port, Damietta Port, East Port Said, and Suez Canal Zone) were chosen based on the potential become green/low-carbon hydrogen clusters as identified within the framework of this project.



Five locations

The analysis provided the following conclusions:

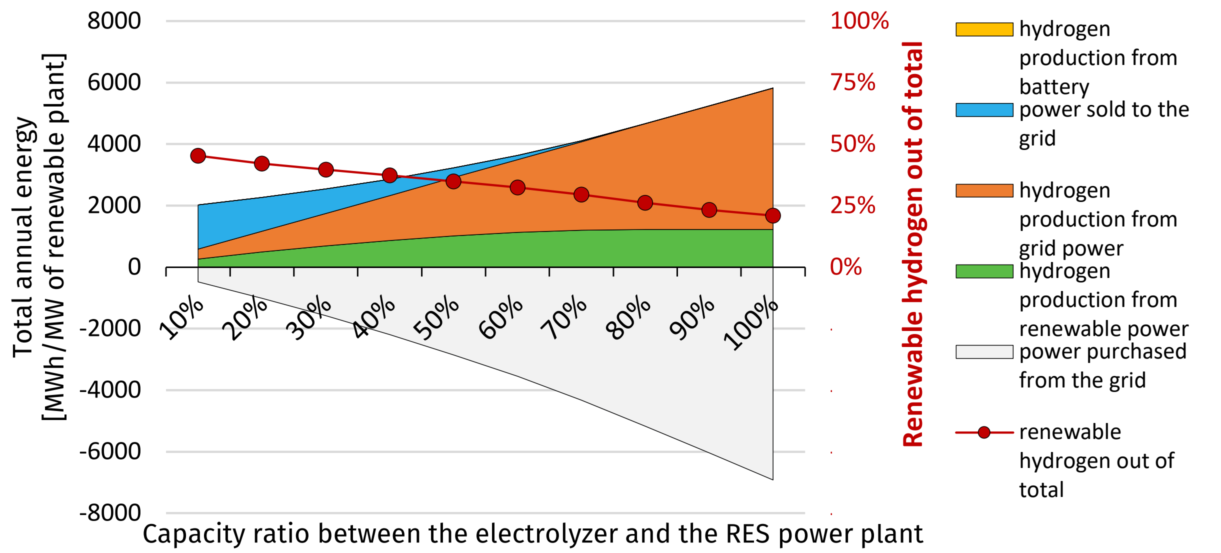
- **Wind** is the dominant source. PV is only relevant in site 5;
- **Site 3** offers the best values for LCOH. Site 5 offers the worst values for LCOH;
- **The minimum LCOH configuration** is Wind, 10% Min load electrolyzer; with/without battery, EC/RES=10% with revenues from electricity sold to the market;
- To have/not have a battery does not impact much on the LCOH in most cases;
- **Revenues** make a big difference on the LCOH. With no revenues from electricity sold to the market, 100 % load electrolyzer and a ratio of EC/RES =100% is needed for the lowest values;

As an example, the figure below that refers to the Alexandria site, illustrates some general trends that can be derived by observing all cases.

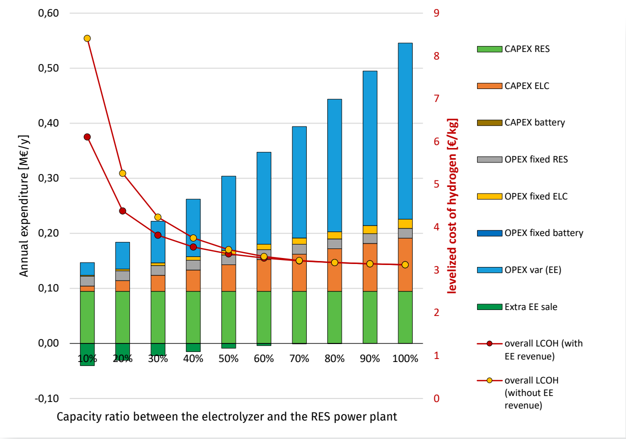
- Wind power produces more renewable hydrogen than solar power;
- Solar power requires grid electricity during night periods, while wind power can obtain 100% renewable hydrogen production;
- Battery has limited impact on wind power but can slightly increase renewable hydrogen share for intermediate capacity ratios.
- When the minimum load factor for electrolyzers is low, renewable hydrogen production is higher but overall hydrogen production is lower; Conversely, at full load operation, renewable H_2 production is the same for any capacity ratios above 50% (i.e., electrolyzer capacity over power plant capacity), while the hydrogen obtained with power from the grid increases with the capacity ratios;
- Revenues are key for low LCOH. For those cases in which the capacity of the electrolyzer is lower than the instant power produced by the renewable source, some “excess” renewable electricity is produced (i.e., it is not converted to hydrogen). Such excess electricity may be sold to the grid bringing revenues to the hydrogen producer. In those instances, selling electricity is more remunerative than producing hydrogen; and thus, low electrolyzer capacity ratios compared to the installed wind power are preferred (as they show lower LCOHs).

For the evolution of LCOH with the same configurations (example in the figure below), results emphasize the following **interesting trends:**

1. Presence of batteries increases the proportion of renewable hydrogen over the total, particularly with solar power, while negatively impacting on the LCOH.
2. When considering revenue from surplus electricity sale, low capacity ratios of electrolyzers over renewable energy power plants are preferred for wind power as electricity sales are more profitable than hydrogen production.
3. But, without considering revenues the lowest LCOH for wind power is achieved with 50% capacity ratio (low minimum load of the EC); and with high-capacity ratios for cases with high minimum loads. This trend is observed in all solar cases, regardless of the operation mode.



Total annual hydrogen and electricity production (left axis) and share of renewable hydrogen (right axis); case of Alexandria site, solar PV power generation, constant full-load operation of electrolyzer, without battery.



Total annual expenditures for hydrogen production (left axis) and levelized cost of hydrogen (right axis); case for Alexandria site, solar power generation, constant full-load operation of electrolyzer, without battery.

To sum up, results show that **electrolysis-based hydrogen production in Egypt could have relatively low costs** compared to other case studies.

In the Alexandria case, the LCOH results at present time are around 3.0-3.5 €/kg with wind and 3.2-5.0 €/kg with PV, when enabling a partial electricity input from the electric grid, without considering the revenues from sold electricity (this could reduce the LCOH by 0.5-1.0 €/kg). However, with the most optimal configurations derived from the analysis, lower values are achieved (with no electricity revenues, 100 % Min load electrolyzer and a ratio of EC/RES =100%), as displayed in the following table:

Product	Range (€/kg) – Present	Range (€/kg) - 2030	Range (€/kg) - 2050
Hydrogen	2.59 - 3.11	2.07 - 2.61	1.44 - 2.36
Ammonia	0.78 - 0.87	0.69 - 0.82	0.60 - 0.83
Methanol	0.90 - 1.06	0.79 – 0.91	0.69 - 0.83

Note: As pre-feasibility work has been conducted for these studies, it is important to underline that this analysis did not fully consider GHG emissions. Some configurations took into account grid power to optimize LCOHs, which can come from CO_2-emitting sources. Hence, these are guiding figures to continue deepening further.

Green/Low Carbon Hydrogen Business Models

Different business models for the hydrogen sector within the Egyptian context can be proposed taken into account the **time perspective**: short-, medium-, and long-term models depend on several factors, including:

- Egypt aims to be one of the largest exporters of green hydrogen in the region.
- Current infrastructure and means to transport and export of green hydrogen and derivatives.
- Future demand on green hydrogen/derivatives.
- Maturity of technological applications for the use of green hydrogen.
- Opportunities for local industries decarbonization.

Egypt is currently undertaking several actions towards the development of low carbon hydrogen initiatives and projects. Announced **projects are for green hydrogen / ammonia / e methanol production and are Public Private Partnerships** between a number of government agencies, and leading global companies and alliances in the production of renewable energy, as mentioned above. This Public-Private Partnerships model is needed as a de-risking mechanism to finance institutions and companies to provide the investments needed at a scale sufficient to support market development. So, considering the time perspective and in line with the national low-carbon hydrogen strategic framework, the following vision is proposed:

- **In the short term**, the country can focus on the production of green ammonia and methanol for export and targeting international markets. Green ammonia can play a crucial role in many potential target applications and sectors: it will enable the production of clean fertilizers, and potential decarbonization of food production. It can also be used in combustion engines of deep-sea vessels helping the decarbonization of the maritime shipping sector. And it will allow the decarbonization of other chemical products where ammonia is used as feedstock. The production of green methanol will rely on the production of electrolytic hydrogen from renewable energy sources and CO_2 that is sourced from bioenergy to be used as shipping fuel.
- **In the medium-term**, Egypt can involve the production of green and low-carbon hydrogen that could be utilized as a decarbonization pathway for hard to abate industries for "local off takers". Regarding exports, as the EU Carbon Border Adjustment Mechanism (CBAM) will demand rigid conditions on the sustainability associated to hydrogen origins in the medium-term, Egypt will have to decarbonize as much as possible its hydrogen economy to comply.

It will also involve building a strong foundation for the industry, including the development of production facilities, infrastructure, education and training programs, a solid regulatory framework, public awareness campaigns, and partnerships with international companies and governments.

And finally, creating **a long-term business** vision for green hydrogen requires a strategic and comprehensive plan that takes into account technological advancements, global trends, and changing customer demands. It requires a comprehensive and integrated hydrogen ecosystem that addresses all links of the value chain. The long-term scenario mainly depends on the readiness of needed infrastructure:

- Exporting green hydrogen through pipelines, LOHC, or as liquefied Hydrogen.
- Exporting Renewable Electricity for electrolyzers localized abroad (electron transfer).
- Expansion of green hydrogen use locally either through dedicated production or through transmission as blended within the local natural gas pipelines.

Looking at potential business models along the overall hydrogen supply chain that are **suitable for the Egyptian context, ten classes are identified and investigated, with 22 cases.** These refer either to the production and transportation of hydrogen or to the end-use sectors. In both cases, hydrogen can be treated in pure form or as derivatives.

Three different technological routes can be identified involving the production of H_2 and its transport via pipeline, ship, or conversion to different energy carriers.

1. Projects concerning the production and transportation via pipeline:

Source

The Holland Hydrogen I project in the Netherlands

The Port of Rotterdam is already a potential location for Egypt's transport of Green Hydrogen/Ammonia. Therefore, Hydrogen and Ammonia can be exported there by 2025 and be jointly transported through this pipeline to increase the capacities in the chemical park and continue the expansion.

Source

The Nordic Hydrogen Route project in Finland and Sweden

This will increase the hydrogen market and allow South and Western European countries to increase ammonia and hydrogen imports from Egypt to inject it through various connected pipelines in Europe.

Source

The Southern Gas Corridor project in Azerbaijan

The existing natural gas pipeline that Azerbaijan is evaluating to repurpose for hydrogen/ H2-NG blend transport can be connected to this pipeline to cover more countries and expand the market.

Source

HyPerLink in Germany, Netherlands and Denmark

Netherlands and Germany are two of the biggest potential off takers for taking ammonia from Egypt. So, this will help in accelerating the projects in Egypt.

2. Projects concerning the production and transportation via ship are investigated in the form of liquefied hydrogen:

Hydrogen Energy Supply Chain (HESC), in Australia and Japan

This will not have a noticeable impact for the green hydrogen market in Egypt as it focuses on grey and blue hydrogen, but it will stimulate the hydrogen market in general.

Source

The Norwegian Topeka

This may stimulate other vessel companies to transform to ammonia or hydrogen bunkering which can offer great lessons learned for green bunkering in Egypt through Suez Canal & Ain Sokhna Port.

Source

3. Projects concerning the production and transportation via ship are investigated in the form of liquid organic hydrogen:

The SPERA Hydrogen project in Japan and Brunei

This may be a game changer to transport liquefied hydrogen to Europe instead of Ammonia and use it directly in industries. Egypt can experiment with liquid organic hydrogen and assess its viability for transportation purposes.

Source

4. Projects concerning the production and transportation via ship are investigated in the form of ammonia:

Western Green Energy Hub, WGEH in Western Australia

This will increase hydrogen market and create competitive pricing of LCOH of exporting to Europe and Asia specifically.

Source

Green Energy Oman (GEO)

Oman is a big competitor to Egypt and is taking fast steps to realize hydrogen projects which have high potential like the Egyptian ones. So, Egypt should move faster to secure off-takers with good pricing.

Source

Source

Asian Renewable Energy Hub (AREH), in Western Australia

Australia will be a strong competitor to Egypt for exporting mostly to the Asian markets.

5. Projects concerning the production and transportation via trains:

Source

H_2IseO Hydrogen Valley in Italy

This may be a great push for Italy to buy ammonia and hydrogen from Egypt through Vessels at the beginning, and later create a pipeline if needed.

6. Projects concerning the supply of hydrogen to mobility sector: road vehicles

Serra Hydrogen Valle in Italy

This will motivate and accelerate the collaboration between Egypt and Italy in terms of exporting Hydrogen from Egypt either through vessels or pipelines. Italy and Egypt have a long-term relationship in mega projects, so it will be easy to continue this collaboration in hydrogen projects.

Source

Hydrogen Fuel for Paris, in France

This will not have a significant impact on Egypt, but will increase both the hydrogen market and value chain in Egypt. If Egypt has competitive hydrogen to export, it could access the French market

7. Projects concerning the supply of hydrogen to steelmaking:

Source

HYBRIT, in Sweden

This can be a good case study to be checked to apply it in the steel's plants in Egypt for their decarbonization plans given the success of this pilot project.

HyDeal in Spain

This will stimulate the market and some companies working in Hydrogen projects in Egypt can join that platform with their projects in Egypt and they will be competitive and fast runners as mostly of these projects intend to start operation and production before 2030.

Source

8. Projects concerning the supply of hydrogen to industry, chemicals:

HEGRA, in Norway

This can be a perfect case study to be implement in ammonia plants in Egypt and learn from the experience and how that will affect their end-product, and pricing.

Source

Puertollano green hydrogen plant, in Spain

Some Egyptian developers such as Orascom/Fertiglobe can approach them and take part in that project given their current experience in a similar project.

Source

9. Projects concerning the supply of hydrogen to industry, e-fuel production:

Power-to-Methanol Antwerp B.V. in Belgium

This will stimulate the market for green methanol bunkering and the industrial applications of green methanol. Egypt is still studying that aspect with Maersk, so this will be of great help to take further steps in the matter despite sourcing the needed biogenic carbon dioxide which is challenging.

Source

Finnfjord e-methanol project, in Iceland

Although this will not be green methanol, however, it has great potential for some heavy industries in Egypt that emits substantial quantities of CO_2. This can be utilized to produce other products like methanol and blue ammonia. So, it will be a good case study to follow.

Source

10. Projects concerning the supply of hydrogen to industry, glass production:

Source | NickyPe | Pixabay

H_2GLASS project, in the European Union (24 partners)

It will be a good reference for Glass and Aluminum Egyptian companies working on their decarbonization plans. It may motivate the Egyptian government to provide them some incentives as well if this project succeeds.

Source

Schott, Encirc and Diadeo in Germany

It will be a good reference for Glass Egyptian Companies working on their decarbonization plans to watch this closely and how they can sell green glass in the future.

Focusing on the Egyptian case, some business models might result more suitable in the short- to mid-term. Among these, **the development of an exporting route of green molecules (e.g., ammonia, methanol) is promising**, and it could take advantage of the existing infrastructure built for fossil-based fuels, the know-how in desalination for water provision, and the wide availability of low-cost renewable energy sources.

The attention to international export may not cancel an interest for the decarbonization of the internal demand. Here, hard-to-abate industrial sectors such as the **fertilizer** value chain or **the steelmaking appear to be the best candidates** for the first efforts within the country, in terms of economic investment and policy making.

GHG emissions associated with hydrogen production and reduction potential

Currently, 95% of the world's hydrogen production is derived from the reforming of natural gas or other hydrocarbons.

The Carbon dioxide emissions associated with the production of Gray Hydrogen can be separated into two streams:

1. The first emission stream from the SMR process in which **methane is converted to carbon dioxide and hydrogen**; and
2. The second emission stream is linked to the **energy used to generate heat & high pressure** needed for the SMR process.

A reference value of 9.5 kg of CO_2 is associated with the production of 1 kg of gray H_2 which depends on many variables associated with the status of the production facility. This does not include upstream fugitive emissions which could substantially increase the carbon intensity. An accurate estimation of the carbon footprint associated with hydrogen production from natural gas requires accounting for the various sources of emissions **through the whole life cycle**:

» The construction and commissioning of facilities for hydrogen production and carbon capture (negligible for blue hydrogen).

» The extraction and transportation of natural gas (upstream emissions).

» The hydrogen production process (e.g., SMR or ATR).

» The carbon capture process including capture, transport, and storage.

» The production of the other energy vectors used (e.g., electricity).

As presented earlier, the Egyptian industrial sector natural gas consumption was close to a quarter of Egypt's domestic gas use (23%), and the fertilizer industry alone accounted for about 46 % of that, followed by the petroleum sector (9.1 %) and iron and steel industry (3%); and cement (less than 0.5%).

According to Worldmeter, in 2016, fossil CO_2 Emissions were 219,377,350 tons or 219 MT, a 5% higher than the year before. In this context, the Egyptian industrial sector is the third-largest contributor to GHG emissions from energy use (28%), which requires industries to adopt measures to reduce its related GHG emissions.

Based on the total estimation of about **1.825 million tons of grey hydrogen produced** and consumed in Egypt, it can be derived that an average of **17 million tons of CO_2 were emitted** in the atmosphere. This represents 6% of Egypt's present total CO_2 emissions that would be difficult to avoid or reduce. The ammonia production used around 179.6 BSCF associated with the emission of 9,895,960-ton CO_2, making ammonia production in the country 3% of the total. Therefore, low carbon hydrogen would have a crucial role in reducing emissions in Egypt's hard-to-abate industries.

Blue hydrogen production is based on the same processes as grey hydrogen - Steam Methane Reforming (SMR) and Auto Thermal Reforming (ATR) - with the addition of carbon capture and storage (CCS), so how carbon intensive blue hydrogen depends on how much CO_2 can be captured. Depending on the process selected blue hydrogen can have a carbon intensity of between **0.8 – 4.4 kg CO_2/kgH_2.** Auto-Thermal Reforming (ATR) process is well established and is now considered to be the preferred technology, due to improved efficiency and capture rates (considered to be >95% this compares to capture rates from SMR at around 90%).

Green hydrogen is produced from water electrolysis has an associated carbon footprint of **less than 3 kgCO_2/kgH_2** according to EU directive on the production of renewable hydrogen, hydrogen- based fuels or other energy carriers of non-biological origin (RFNBO).

Annex

Annex 1: Hydrogen demand in international markets

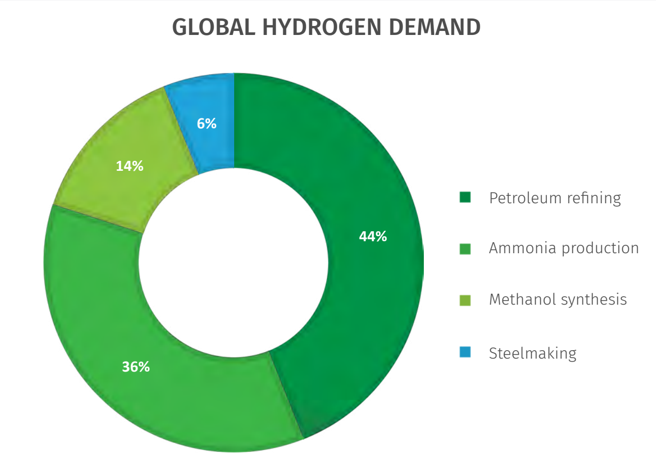
Hydrogen demand is currently confined in the industrial sector, where it is used as a feedstock for the production of basic chemicals or in refineries. In particular, Global Hydrogen demand reached **more than 94 Mtons in 2021**, 5% more in comparison with 91 Mtons in 2019.

This demand is split between petroleum refining (44 MtH_2/y), ammonia production (34 MtH_2/y), methanol synthesis (15 MtH_2/y), and steelmaking (5 MtH_2/y), while the production is mostly based on steam methane reforming (SMR) of natural gas.

Hydrogen demand equals to 630 Mt of direct CO_2 emissions or 7 % industrial emissions in 2021.

With the "RepowerEU" package, the European Union pledged for a 55% reduction of greenhouse gas (GHG) emissions compared to 1990 levels by 2030. Regarding hydrogen, the European roadmap estimates a total demand of 16.2 MtH_2/y, with the sectorial subdivision shown in the table below. In parallel, the European Commission estimates that **half the demand** can be produced domestically, while the remainder **can be imported**, either via pipeline or in the form of derivatives (e.g., ammonia, methanol). EU neighbouring countries such as Egypt could cover this demand (partially).

Owing to the necessity to reduce dependence on Russian imports, the European Union has allocated more resources and attention towards medium-term decarbonization targets than the rest of the world. Long-term estimations of hydrogen demand typically target the year 2050, and generally derives from the carbon neutrality objective. Given the increasing political consensus on such goal, a range of international studies have been conducted to address long-term scenarios. European authorities estimate that hydrogen could cover up to 24% of the total energy demand, supported by an electrolysis capacity of 500 GWe. In parallel, projections of the World Energy Council indicate that the hydrogen demand in Europe could reach 60 MtH_2/y, about half of which are expected to be imported.



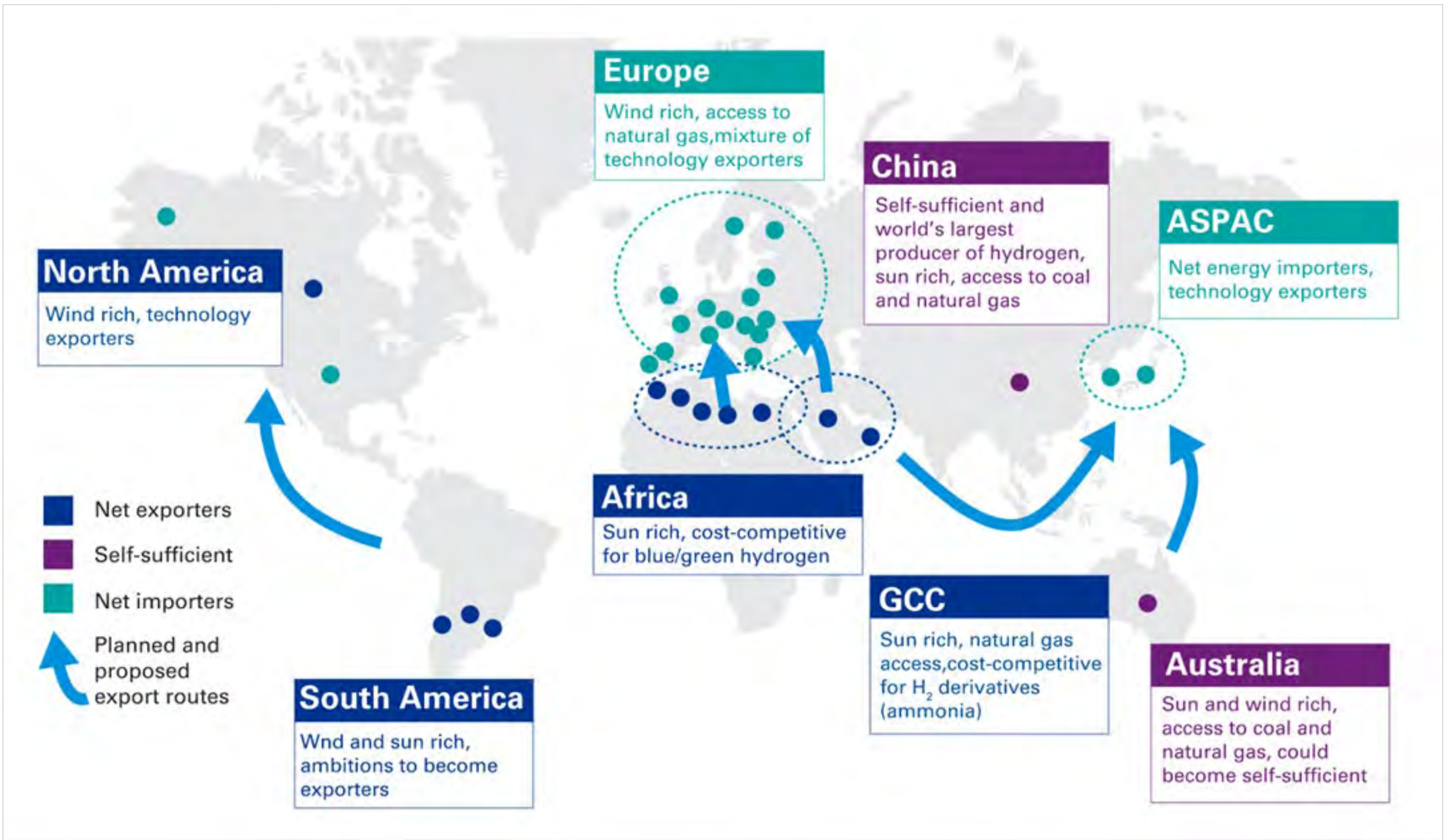
Sector	Hydrogen demand in 2030 [kt of H_2]
Refineries	2273
Industrial Heat	3629
Transport	2319
Petrochemicals (Ammonia)	3232
Blast furnaces	1520
Synthetic fuels	1788
Power generation	105
Blending	1335
Total	16,200

DNV's "Energy transition outlook 2021" estimates that the global hydrogen demand could exceed 250 MtH_2/y, with relevant uses in refineries, ammonia production, and heat generation. In 2022, the International Renewable Energy Agency (IRENA) provided an upward revision of the forecasted demand in 2050, with a value of over 400 MtH_2/y. China is expected to lead the global consumption (102 MtH_2/y), followed by the European Union (75 MtH_2/y), countries of the MENA region (37.5 MtH_2/y), India (35 MtH_2/y), and USA (33 MtH_2/y). Due to the limited local availability of renewable energy sources and the high energy demand, Europe and Japan are projected to become net importers, while Africa, South America, and MENA countries will likely be the main exporters, and Australia and China may be self-sufficient (see figure below).

Thanks to its well-established gas infrastructure, Egypt holds the **potential to become the energy export hub of Eastern Mediterranean.** The country features two LNG plants with a combined capacity of 17.3 bcm per year. These represent a key strategic and commercial international asset, as they are used both to export the domestic natural gas production and to liquefy and ship Israeli gas.

Building on the momentum of its expanding gas sector and exploiting its rich renewable energy sources endowment, Egypt has the capability to adapt its energy strategies to the transition towards decarbonization, as it can leverage on the infrastructures and on the strategic positioning to become a hydrogen exporter. Driven by the need to diversify gas supply, the EU is becoming Egypt's main commercial partner, and the import of hydrogen from Egypt has been included in the EU decarbonization and diversification of supply strategy.

The production of low-carbon ammonia appears as a promising and simple option for hydrogen **shipping to Europe**, since Egypt is already **a major exporter of ammonia**, and it can take advantage of an existing well-functioning **port infrastructure**. In this scenario, the main destination countries are likely to be Italy, Spain, and France, which are currently the main importers of Egyptian ammonia and LNG. Possible market expansions could involve the Netherlands, Germany, and Greece, as they feature the main freight ports in Europe. Outside the EU, possible destinations include Turkey, Pakistan, and Japan, with which trade relations have already been developed. Given the urgency of European climate targets, the availability of an established shipping infrastructure makes this option preferable to the greenfield development of a pipeline connection between Europe and Egypt, considering that it would require significant capital expenditures and that it may encounter geopolitical barriers.



Global hydrogen hot spots and corridors (from KPMG. Source)

Annex 2: International regulatory frameworks, including standards

The path towards a widespread diffusion of hydrogen use relies on the development of appropriate standards, from both the technical and the regulatory point of view. The ISO developed regulations for various hydrogen technologies, covering a good part of the value chain. Hydrogen production via low-temperature electrolysis is regulated by the ISO 22734, which defines the construction, safety, and performance requirements. The ISO 22734 is currently being revised to cover aspects related to the operation under dynamic loads in combination with intermittent power generation. Various regulations have been developed for hydrogen uses. Specifically, the ISO 14687 sets the quality specification for PEM fuel cells to 99.97% purity, whereas the ISO 19885 addresses fuelling of hydrogen vehicles, also covering heavy-duty vehicles. New ISO technical committees are expected to be set up in the areas of rail, aviation, and maritime applications, which have not been addressed yet.

Although hydrogen carriers, such as ammonia, methanol, and liquid organic hydrogen carriers (LOHC), are expected to represent a notable market share, they are not directly addressed in hydrogen regulatory frameworks. Indeed, regulations currently in place considers these carriers as hazardous materials, setting out the requirements for their transport and handling. Examples are the Dangerous Goods Regulation in the European Union, the Hazardous Materials Regulations enforced by the Department of Transportation in the United States, the Transportation of Dangerous Goods Act in Canada, and the Australian Dangerous Goods Code in Australia.

Most of the regulatory activity so far has been focused on establishing criteria that production methods must meet to classify the produced hydrogen as "low-emission", fixing a maximum threshold for the amount of GHG emissions allowed. As the table shows, threshold values range between 2 and 3 $kgCO_2eq/kgH_2$ depending on the region. This approach aims at overwriting the colour scheme, as all form of hydrogen are included, for instance produced electrolysis powered by renewable electricity (referred to as "green hydrogen") or via steam reforming or coal gasification equipped with CO_2 capture and permanent sequestration (referred to as "blue hydrogen"). Moreover, the European Commission just finalized (1st quarter 2023) the introduction of strict criteria to classify hydrogen as **"renewable hydrogen"**: additionality (renewable electricity used for electrolysis must be an additional quantity with respect to that of existing plants), contemporaneity of operation (the generated renewable electricity must be consumed by the electrolysis in the exact time frame on hourly basis, to avoid grid unbalances), and absence of grid congestions (hydrogen production fed with renewable electricity must not interfere with the proper functioning of the electric grid). Finally, the European Commission has also developed a methodology for the assessment of lifecycle GHG emissions of RFNBOs. The ISO/TC 197/SC 1, instead, defines a methodology specifically for hydrogen, covering production, conditioning, and transportation.

Country/ region	Threshold [$kgCO_2eq/kgH_2$]
United Kingdom (link)	2.4
European Union (link)	3
United States (link)	2

Overview of thresholds for the amount of GHG emissions allowed in the production of low-carbon hydrogen.

There is currently a lack of unified regulation regarding the presence of hydrogen in the gas mixture flowing in the natural gas networks. The existing limits reflect the possible material problems of the pipes in presence of hydrogen (embrittlement is currently under study by multiple industrial and research entities), the willingness to avoid moving around inert gases, and the need to guarantee stable feed to the end uses. The latter is expressed by the Wobbe index (defined as the ratio between the higher heating value and the square root of the relative density of the fluid), which is commonly used as indicator of the interchangeability of fuel gases.

National gas grid codes typically feature a limit hydrogen fraction. Among European countries, Germany features the highest limit fraction, with a recently confirmed value of 20 %mol. In the other cases, the limit hydrogen fraction ranges from 0.5 %mol to 6 %mol. Overall, studies with hydrogen blending up to 20 %mol have been successfully completed in various countries and with end uses in both the industrial and civil sector, while different projects aiming at investigating hydrogen fraction up to 100%mol are planned to be operational in the next years. In this regard, most TSOs in Europe have introduced hydrogen-ready policies, so that any new installation is suitable to hydrogen, according to the standards developed by regulation entities. Such standards are based on the principles of the ASME B31.12:2019, which defines the requirements for materials, wielding, brazing, heat treating, forming, testing, inspection, examination, operation, and maintenance for hydrogen transport in pipelines.

Advancements have been made also on market regulations for hydrogen and its deployment in the energy system. Australia is planning to extend the natural gas regulatory framework to hydrogen and other renewable gases. The European Commission presented a regulation proposal for the establishment of a hydrogen market, envisaging the creation of a network of hydrogen operators to promote the development of a dedicated hydrogen infrastructure, cross-border coordination, and the elaboration of specific technical rules. The European Commission expects to adapt the regulatory framework by 2030, reflecting the development of the hydrogen market. The Netherlands government is planning to organize a hydrogen market by leaving production activities unregulated and instead regulate hydrogen networks, appointing a state-owned transmission system operator.

Both governments and private organizations are working on **the development of hydrogen certification schemes**. The world's first clean hydrogen certificate has been awarded by the German certification body TÜV Rhineland to a project for the production of green ammonia in Oman. Other certifications schemes have been introduced or studied in Australia, Finland, Spain, Netherlands, United Kingdom, and South Korea as well as in organizations like DNV, and ISCC. The CertifHy project, supported by EU's Clean Hydrogen Partnership, is one of the most advanced examples of green hydrogen certification systems.

Governments and institutions are developing a set of **policy tools to mitigate investment risks** and foster the development of a hydrogen market. Support to hydrogen-related investments have been provided through the Bipartisan Infrastructure Law and the Defense Production Act in the United States and through the Important Project of Common European Interest (IPCEI) scheme in Europe, while tax incentives are implemented in the United States, Germany, United Kingdom, Austria, Brazil, and Colombia.

The past few years have witnessed positive steps towards the definition of a stable hydrogen regulatory framework, with the active interest and involvement of numerous stakeholders. However, given the urgency of climate targets, increasing effort is required to accelerate the progress, widening the attention to the whole hydrogen value chain. Overall, a coordinated and comprehensive approach is essential to ensure the successful deployment of hydrogen, considering that its implementation is part of a broader transition towards a highly integrated system.


Egypt's location, abundant renewable energy resources, natural gas infrastructure, and associated skills are combined with sectoral enabling policies, strategies for water desalination, and industrial know-how in hydrogen and ammonia production and related exports. All this places Egypt in a unique position to develop a front-leading hydrogen economy for Egypt and potential neighbouring markets.

For more information on the UNIDO's Global Programme:

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