# POWER-TO-[X]

## GREEN HYDROGEN OPPORTUNITIES IN JORDAN


Report to the Friedrich-Ebert-Stiftung | January 2022

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## Green Hydrogen Opportunities In Jordan

**Prepared for:**
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Jordan

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**January 2022**

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## About Friedrich-Ebert-Stiftung

Friedrich-Ebert-Stiftung is the oldest German political foundation and advocates for the advancement of social democracy. Through its Jordan-based Regional Climate and Energy Project MENA, it brings together government representatives with civil society organizations, supports research, and provides policy recommendations to promote and achieve a socially just energy transition and climate justice for all in the MENA region.

## About Royal Scientific Society / National Energy Research Centre

The Royal Scientific Society (RSS) is an independent non-governmental, not-for-profit multidisciplinary science institution established by Royal Charter. Founded in 1970 as a national organisation to actively advise and support the development of Jordan with sound technical and policy advice, and consultations. The RSS undertakes specialised and accredited testing, research work with local industries and universities, consultations for the private and public sectors, and works in partnership with regional and international organisations. Since its inception as a national and independent organisation, the prime objectives of the RSS have been to protect human health and safety, to safeguard the environment, and to contribute to sustainable economic development.

National Energy Research Centre (NERC), which is part of the Royal Scientific Society (RSS), was established in Amman for the purposes of research, consultancy, development, and training in the fields of new and renewable energy. It raises the standards of energy use in the different sectors and promotes the utilization of renewable energy in Jordan.

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# LIST OF ACRONYMS

| | |
|---|---|
| **APU** | Auxiliary Power Unit |
| **BTU** | British Thermal Unit |
| **C1** | Molecules with a single carbon atom |
| **CAPEX** | Capital Expenditures |
| **CCS** | Carbon Capture and Storage |
| **CCU** | Carbon Capture and Utilization |
| **CGEM** | Confédération Générale des Enterprises du Maroc |
| **CHP** | Combined Heat and Power |
| **COVID-19** | Coronavirus disease 2019 |
| **CSP** | Concentrated Solar Power |

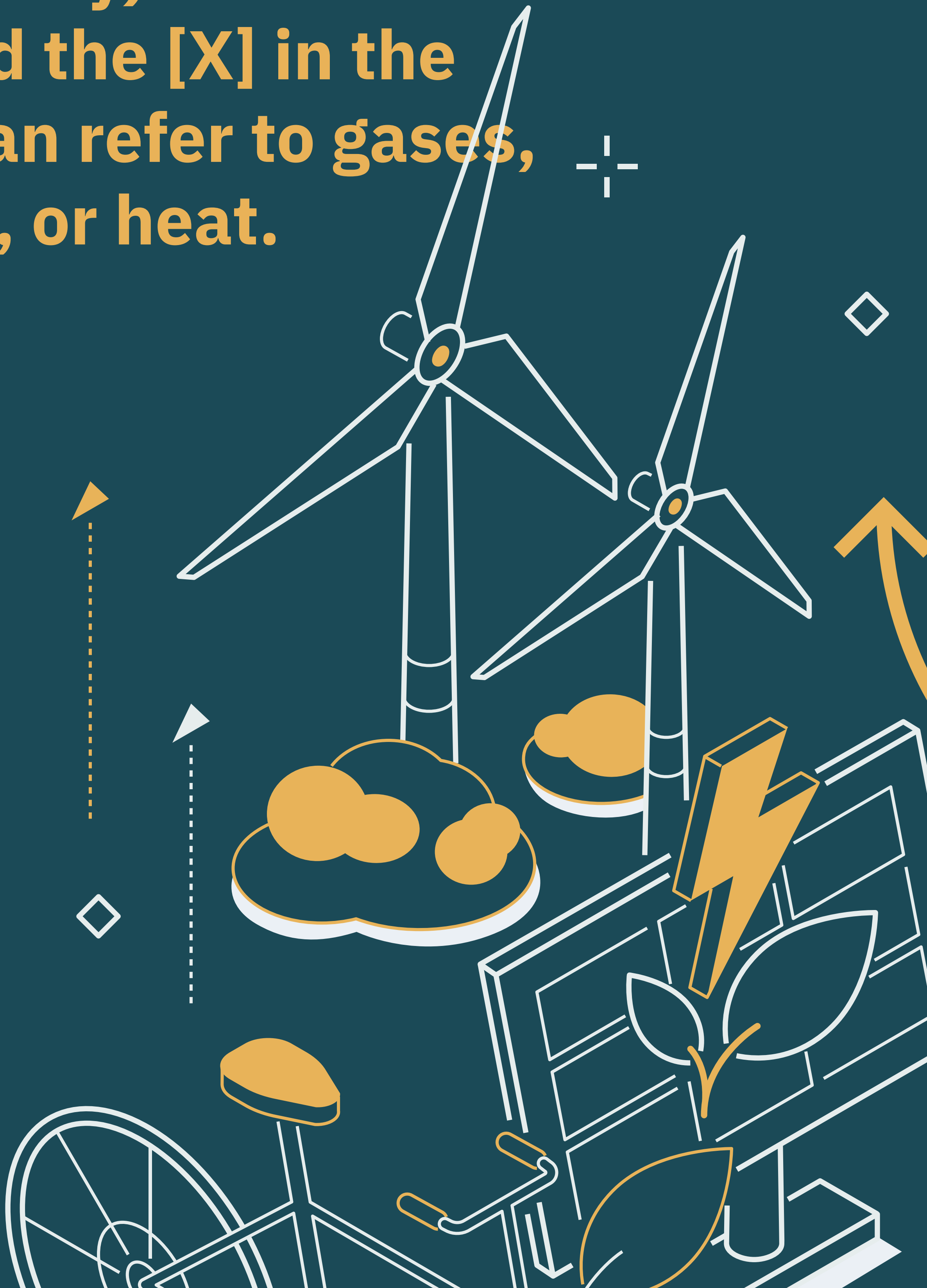
| | |
|---|---|
| **EBRD** | European Bank for Reconstruction and Development |
| **EHB** | European Hydrogen Backbone |
| **ESP** | Education Strategic Plan |
| **EU** | European Union |
| **EUR** | Euro |
| **EV** | Electric Vehicle |
| **FCEV** | Fuel Cell Electric Vehicle |
| **G** | Specific Gravity |
| **GHG** | Greenhouse Gas |
| **Green H2A** | Green Hydrogen and Applications |
| **HHV** | Higher Heating Value |
| **ICE** | Internal Combustion Engine |
| **IEA** | International Energy Agency |
| **IRENA** | International Renewable Energy Agency |
| **IRESEN** | Institute of Research in Solar Energy and New Energies |
| **KfW** | Kreditanstalt für Wiederaufbau |
| **LFL** | lower flammability limit |
| **LOHC** | Liquid Organic Hydrogen Carriers |
| **Masen** | Moroccan Agency for Solar Energy |
| **MEMR** | Ministry of Energy and Mineral Resources |
| **MENA** | Middle East and North Africa |
| **MOF** | Metal-Organic Framework |
| **NCGH2** | National Commission of Green Hydrogen |
| **NEPCO** | National Electric Power Company |
| **OCP Group** | Office Chérifien des Phosphates |
| **ONEE** | Office National de l’Electricité et de l’Eau Potable |
| **ONHYM** | Office National des Hydrocarbures et des Mines |
| **OPEX** | Operational Expenditures |
| **PAREMA** | Moroccan-German Energy Partnership |
| **PHEVs** | Plug-In Hybrid Electric Vehicles |
| **PtX** | Power-to-[X] |
| **PV** | Photovoltaic |
| **R&D** | Research and Development |
| **SMR** | Steam Methane Reforming |
| **STP** | Standard Temperature and Pressure |

| | |
|---|---|
| **TSO** | Transmission System Operator |
| **UFL** | upper flammability limit |
| **UM6P** | University Mohammed VI Polytechnic |
| **UNESCO** | United Nations Educational, Scientific and Cultural Organization |
| **US** | United States |
| **USD** | United States Dollar |
| **VRE** | Variable Renewable Electricity |

# LIST OF UNITS AND SYMBOLS

| | |
|---|---|
| $C_6H_6$ | Benzene |
| $CH_3OH$ | Methanol Molecule |
| $CH_4$ | Methane Molecule |
| **CO** | Carbon Monoxide Molecule |
| $CO_2$ | Carbon Dioxide Molecule |
| **g** | Gram |
| $H_2$ | Hydrogen Gas |
| $H_2CO$ | Formaldehyde |
| $HCO_2H$ | Formic-Acid |
| $H_2O$ | Water Molecule |
| **kg** | Kilo Gram |
| **kJ** | Kilo Joule |
| **kWh** | Kilo Watt Hour |
| **MJ** | Mega Joules |
| **mol** | Unit for Molecular Quantification |
| **Mt** | Mega Tonne |
| **MW** | Molecular Weight |
| **MWh** | Mega Watt Hour |
| $N_2$ | Nitrogen |
| $NH_3$ | Ammonia |
| $O_2$ | Oxygen Molecule |
| **scf** | Standard Cubic Foot |

**The concept involves the transformation of renewable energy (electricity) to chemicals [X], and the [X] in the term can refer to gases, liquids, or heat.**



# EXECUTIVE SUMMARY

Power-to-[X] (PtX) technologies can not only play a substantial role in the global energy mix, but they can also mitigate the impact of global warming. These technologies can help in achieving the Paris Agreement's target to keep the earth's temperature rise below 1.5 - 2.0 degrees Celsius. The use of PtX, especially hydrogen ($H_2$), can contribute to decarbonizing the energy, industrial, and transportation sectors, for example. Due to these reasons, PtX technologies have been gaining increased attention.

The German government and the European Union (EU) formed hydrogen strategies to identify green hydrogen as a fundamental element for energy transformation and decarbonization of different sectors. The strategies also aim to limit global warming to two degrees Celsius and to reach carbon neutrality by 2050.

The different applications of hydrogen, one of which being complimentary to renewable energy sources, indicate that hydrogen technologies have evolved in production, storage, and transportation. Hydrogen is identified by different colors. The various colors distinguish between the types of hydrogen and how each one is produced.

On the one hand, there are several drivers for green hydrogen. These include the cost of electricity, the reduction in the electricity cost of renewable energy plants, the decrease in the cost of electrolysis since 2010, and the interest of many stakeholders. On the other hand, the adoption of green hydrogen is hampered by a lack of specialized infrastructure, high production costs, a lack of value recognition, and energy losses.

The Hashemite Kingdom of Jordan imports 91% of its energy supply (MEMR, 2019). The investment in green hydrogen should motivate the government to decrease its fossil fuel dependency and increase renewable energy penetration. Therefore, the development of an integrated policy approach is essential to reach market penetration and overcome initial resistance. However, there are many challenges that Jordan should address. These include the regulatory framework as well as other challenges associated with the implementation of hydrogen applications, such as infrastructure problems, water scarcity, capital expenditures (CAPEX), and operational expenditures (OPEX).

This guide is composed of six chapters. The first chapter defines PtX technologies, hydrogen production, types of hydrogen, and hydrogen applications. The second chapter discusses different types of PtX, whereas the third one focuses on the role that PtX can play in energy transition and decarbonizing sectors such as industry, transport, heat, and feedstock. The fourth chapter reviews the energy status in Jordan and examines the drivers for green hydrogen. The fifth chapter presents the barriers to PtX that Jordan might face, considering its energy status. The final chapter explores main policy recommendations and steps that can be taken to implement a green hydrogen chain across the country.

# WHAT IS POWER-TO-[X] (PtX)?

## 2.1 PtX Definition

PtX, such as Power-to-gas, Power-to-chemicals, or Power-to-fuels, refers to different processes that turn electricity from renewable energy sources (like wind and solar) into heat, hydrogen, synthetic fuels, or chemicals that would be used in different sectors. PtX aims to utilize the environmental and economic potential of renewable energy. The term PtX emerged due to the increasing number and large diversity of applications relevant to it (Burre et al., 2020).

The concept involves the transformation of renewable energy (electricity) to chemicals [X], and the [X] in the term can refer to gases, liquids, or heat. Water-electrolysis is the most well-known technology that produces chemicals out of electricity to create hydrogen and oxygen. Electrolysis has been hailed as one of the most sustainable fuels, seeing as its combustion leads only to the production of water ($H_2O$), which has minimal impact on greenhouse gases (GHGs) emissions.

PtX can decarbonize industries, transportation, and the energy sector. Carbon dioxide ($CO_2$) is an abundant carbon-based feedstock, which can be transformed through PtX technologies to simple compounds with single carbon atom molecules (C1), such as methanol ($CH_3OH$) and methane ($CH_4$). Methanol, for instance, can be used to produce gasoline, diesel, and other chemicals. Therefore, these technologies will reduce carbon dioxide emissions at the source, produce liquid transportation fuels, and allow the storage of renewable energy (Vasconcelos & Lavoie, 2019).

## 2.2 What is Power-to-Hydrogen?

Hydrogen is deemed as one of the simplest, cheapest, and most abundant elements on earth. Hydrogen contains one proton and one electron. Although it does not appear pure by itself in nature, it can be stored and delivered (Satyapal, 2017).
Hydrogen is an energy carrier that can be utilized in different applications, some of which will be discussed in section 2.4. Many processes can be used to produce hydrogens, such as steam methane reforming (SMR), coal gasification, renewable liquid reforming, and electrolysis (Blasio & Pflugmann, 2020), which will be elaborated on in section 3.2.

## 2.3 Types of Hydrogen

Depending on the method of production, the manufacturing of hydrogen may result in carbon byproducts. Color codes are provided to differentiate between the types and approaches in the production process of hydrogen. **Hydrogen colors are differentiated as follows:**

### Black and Grey Hydrogen

Both black hydrogen and grey hydrogen processes throw off carbon waste. The black type of hydrogen-making process uses black coal or lignite (brown coal), the most environmentally damaging, whereas grey hydrogen is produced through natural gas or $CH_4$, using steam methane reformation. However, the GHGs created in the grey hydrogen process are not captured (Nationalgrid, 2021).

### Blue Hydrogen

Blue hydrogen is also created using natural gas or methane through steam reforming. The process joins both natural gas or methane and heated water in the form of steam. Unlike grey hydrogen production, this process includes carbon capture and storage (CCS) to trap and store carbon dioxide. This process is also called "low-carbon hydrogen" since it creates GHG emissions but captures them through CCS (Nationalgrid, 2021).

### Green Hydrogen

Green hydrogen is the ultimate clean hydrogen resource that creates hydrogen fuel without producing GHG emissions. Green hydrogen is the most suitable approach towards complete sustainable energy transition, and it will be the focus of the report. The process to produce it involves using electricity from renewable energy sources, such as solar or wind power, to electrolyze water. Currently, green hydrogen constitutes a small percentage of the overall hydrogen due to the high capital and operational expenses (Nationalgrid, 2021).

### Turquoise Hydrogen

Turquoise hydrogen is relatively new to the color chart and has yet to be proven. Methane pyrolysis is used to create turquoise hydrogen, which is usually used to produce hydrogen and solid carbon. In the upcoming years, this type of hydrogen might prove its value as a low-emission hydrogen, produced by thermal processes that are powered by renewable energy (Nationalgrid, 2021).

### Pink Hydrogen

Pink hydrogen (also referred to as purple hydrogen or red hydrogen) is created through electrolysis powered by nuclear energy (Nationalgrid, 2021).

# 2.4 Hydrogen Applications

According to Bruce et al. (2018), while hydrogen has primarily been used for a variety of industries like petroleum, fertilizers, chemicals, and food, it also has the capability to serve various applications (see Figure 1). Bruce et al. (2018) also state that "if produced using low or zero-emissions sources, ('clean') hydrogen can enable deep decarbonization across the energy and industrial sectors". This is achieved by reducing the consumption of carbon fuels or through stripping GHGs from the atmosphere, among other means. Other applications of hydrogen are in the energy sector, where it is mainly utilized as a heating fuel, to generate electricity, or in transportation (Bruce et al., 2018).

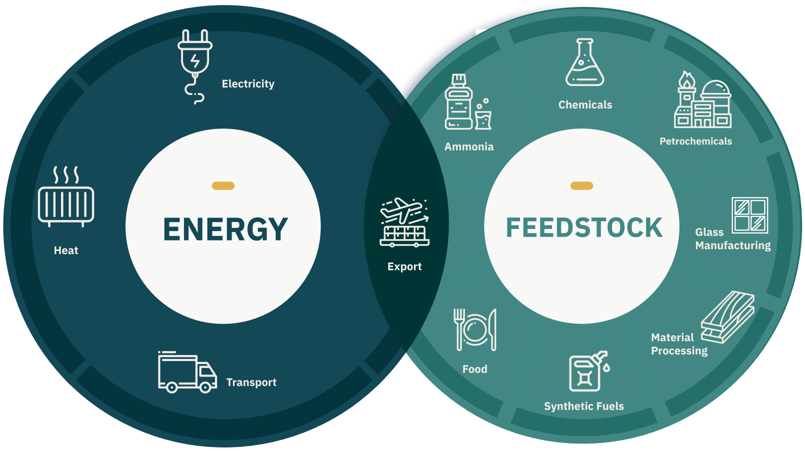



**Figure 1** Applications for Hydrogen (Bruce et al., 2018)

## 2.4.1 Storage and Containment

In most cases, small amounts of hydrogen are stored either in gas or liquid form under pressure. Other methods are also used that allow the hydrogen to be used directly, making it easy to store hydrogen using conventional methods. Furthermore, hydrogen has a wide range of flammability at almost all concentrations in air. Thus, it is deemed as a highly hazardous gas. The gas is stored mostly under high pressures, presenting an explosion and fire hazard.

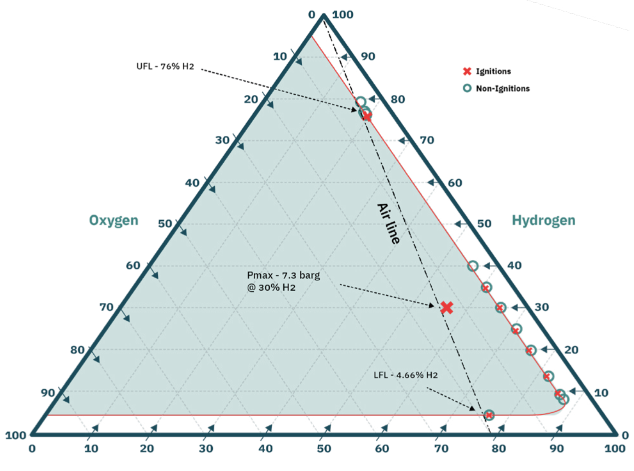



**Figure 2** Flammability Diagram of Hydrogen Gas (the colored region represents flammability) (Frawley, 2021)

A ternary flammability diagram shows the region where a gas becomes flammable with the presence of oxygen and an inert gas (nitrogen ($N_2$)) at different concentrations. In Figure 2, the air-line intersects the flammability region of hydrogen at the two flammability limits, which are referred to as the upper flammability limit (UFL) and the lower flammability limit (LFL). This indicates the range of concentration of hydrogen gas at which it is flammable. Figure 2 shows the flammability range of hydrogen gas; the gas is flammable at almost all conditions in the presence of oxygen. Table 1 illustrates a comparison between hydrogen's flammability limits and that of other gases. The storage of methane gas (methane gas is the main component of natural gas) is significantly safer due to the smaller range of flammability.

Table 1 Percentage Limits of Flammability for Different Gases (Matei et al., 2020)

| The name of the gas | Explosive limits | | Minimum combustion limits | |
|---|---|---|---|---|
| | lower | higher | Gas | Oxygen |
| Methane | 5.0 | 15.0 | 5.9 | 12.2 |
| Carbon monoxide | 12.0 | 74.0 | 13.8 | 6.1 |
| Hydrogen | 4.0 | 74.0 | 4.3 | 5.1 |

## Storage as Compressed Gas or Liquid

Whilst most fuels are stored in liquid form, liquefaction of hydrogen is both costly and hazardous. That is due to both the need for high pressure as well as its small molecular size. The small molecular diameter for hydrogen, as shown in Table 2, means that the gas tends to escape the containment and is an indicator that storage for long periods and under high pressure may cause loss of material. Normally, such gas diffuses from metal by channeling through porosities. Thus, methods of storing hydrogen are different than that of liquid fuels or heavier gases (Freude, 2004).

Table 2 Co-volume Diameter of Different Gas Molecules (Freude, 2004)

| Molecule | Co-volume-diameter d (Å) / 10 Å = 1 nm |
|---|---|
| $H_2$ | 2.76 |
| Oxygen ($O_2$) | 2.93 |
| $CO_2$ | 3.24 |
| Benzene ($C_6H_6$) | 4.50 |

## Adsorption

Hydrogen can be stored on the surface of other materials using a phenomenon called adsorption. The process of adsorption can operate under moderate temperature and pressure. The kinetics of adsorption are quick and fully reversible. A very common material that is being widely developed in synthetic chemistry is metal-organic frameworks (MOF). MOF has a high surface area of approximately 6,000 $m^2/g$, compared to activated carbon and porous polymers of only 3,000 $m^2/g$ (Bimbo, 2019).

## Chemical Storage as Ammonia ($NH_3$)

Ammonia is known to have a high density of hydrogen that can be stored in normal to moderate conditions as gas or liquid. While it eliminates the hazardous conditions like temperature and pressure in order to obtain hydrogen gas, ammonia must undergo a catalytic reaction to decompose (Bimbo, 2019).

Table 3 The Effect of Different Hydrogen Storage Methods on Multiple of its Physical Factors (Bimbo, 2019)

| Storage Method | Liquid Hydrogen | Compressed Hydrogen | Cryogenic Compression | Adsorption in a Porous Material | Metal Hydride | Complex Hydrides |
|---|---|---|---|---|---|---|
| Representative material | - | - | - | MOF-$_{210}$ | $LaNi_5H_6$ | $Mg(BH_4)_2$ |
| Gravimetric % of $H_2$ | 100.0 | 100.0 | 100.0 | 9.0 | 1.5 | 14.9 |
| Operating temperature (in °C) | -253 | 25 | -253 to -196 | -196 | 0-30 | 25-320 |
| Pressure (in MPa) | 0.1 - 1 | 35 or 70 | 10 - 70 | 1 - 5 | 0.1 | 0.1 |
| Volumetric density (in kg of $H_2$ per $m^{-3}$) | 70.3 | 23.2 (35 MPa)<br>39.0 (70 MPa) | 45.0 | 44.0 | 108.0 | 146.0 |

# 2.4.2 Industrial Use

In addition to its application in the energy sector, hydrogen is the main component in many other industries. It is commonly used to produce ammonia, which is a main ingredient of fertilizers, and it is also used for oil refining and steel production. For some industries, hydrogen is produced on site through electrolysis, steam reforming, or as a by-product. Moreover, hydrogen is often used in the food industry to produce hydrogenated fats like margarine as a vegan alternative for butter.

## Steel Production

Steel production is a process of reducing iron ore using coal. An alternative procedure of iron ore reduction using hydrogen is called direct reduction. Using hydrogen, as demonstrated in Figure 3, will produce mainly water, unlike the conventional method that emits carbon dioxide (Sander-Green, 2020).

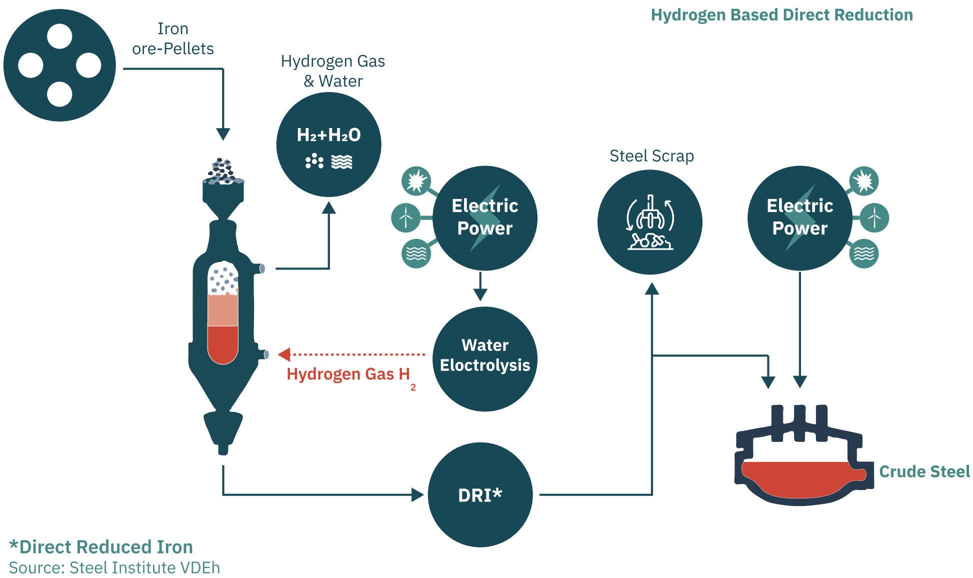



**Figure 3** Direct-Reduced-Iron Production from Hydrogen as an Alternative to Carbon (Coal) (Sander-Green, 2020)

## Food Production

Different types of fats are used in the food industry. Saturated and unsaturated fats are both the main terminology of categorization. The bonds of saturated fats are all saturated with hydrogen. They have a higher melting point and remain solid at room temperature, such as the case with butter. For this reason, they are preferred for producing goods like peanut butter. Saturated fat is produced by a process of hydrogenation of unsaturated fats like plant-based oils. With the presence of a catalyst, hydrogen reacts with unsaturated fats to produce saturated fats (see Figure 4).

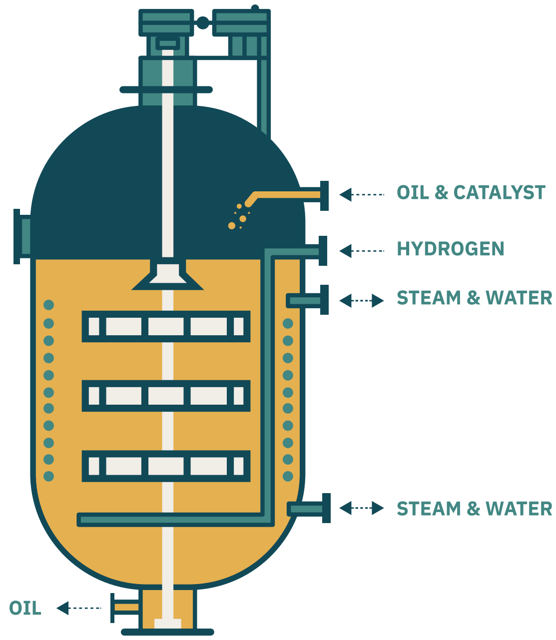



**Figure 4** Hydrogen Usage in the Production of Hydrogenated Fats (Shri Hari Fabtech, 2018)

## Petroleum Refining

Hydrocracking is the process of reducing the oil chain length to create lighter fuels from heavy oils (see Figure 5). In this process, hydrogen plays the role of a reactant. It bonds to the oil chains until the bond breaks, which stabilizes the product fuel (EIA, 2013).

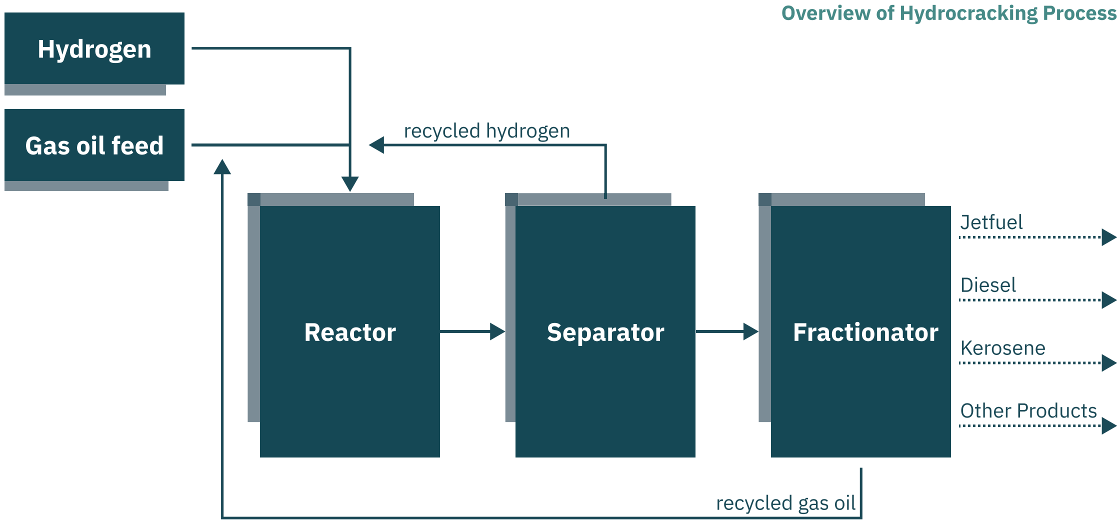



**Figure 5** Hydrogen Usage in Transformation of Heavy Oils to Lighter Oils (EIA, 2013)

## Ammonia and Plant Fertilizers

Ammonia production is the base of nitrogen-based fertilizers. The main feedstock needed to produce ammonia is nitrogen and hydrogen. Both gases react in the presence of a catalyst (see Figure 6).

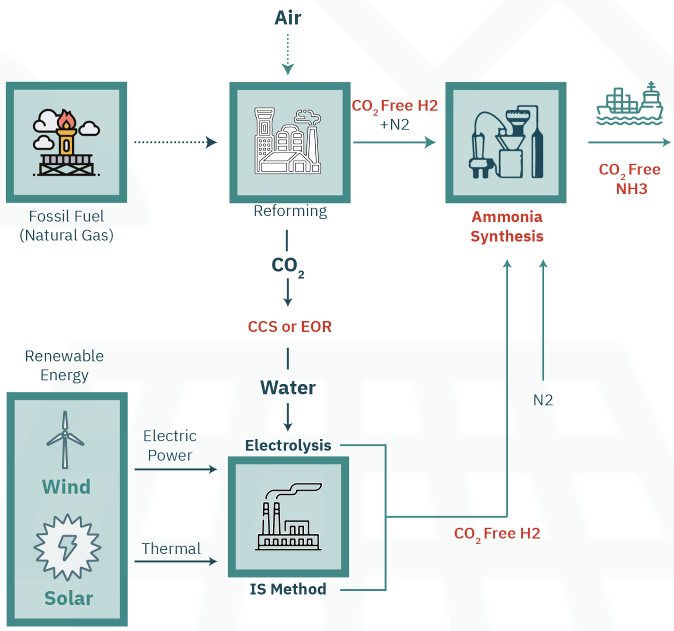



**Figure 6** Ammonia Production from Hydrogen as a Main Reactant (JGC, n.d.)

## 2.4.3 Transportation and Fuel Cells

Transportation technology has always relied on the use of fossil fuels. Although there are vehicles that run on electricity, the cycle has not yet reached a neutral carbon footprint. Also, despite all the available technologies for running vehicles on electricity, depending on batteries does have disadvantages. A battery has a limited lifetime, recycling car batteries is still under development, and charging batteries is relatively slow, in comparison to the time needed to fill a car with fuel. Due to these reasons, hydrogen is deemed as a clean and practical solution (Dufton, 2016).

### ■ Why Transportation?

Seeing as there is growing concern about climate change and its impact on public health, it is essential to manage emissions from transportation. These emissions are mobile and city-centered, thus having a higher impact on public health. Hydrogen can be used in a wide range of applications in transportation. Some such applications include distribution, renewable energy storage, combined heat and power (CHP), and commercial (trucks, aviation, marine, rail, and buses) and noncommercial transportation, such as cars, backup power, auxiliary power, and portable power. It aims to reach a carbon status of near-zero carbon emissions.

**The following impactful results in transportation can be accomplished:**

- Light-duty highway vehicles using gasoline can reduce emissions by 50% to 90%.
- Specialty vehicles can reduce emissions by more than 35%, compared to diesel and battery-powered lift trucks.
- Transit buses can have 1:5 times greater economics than diesel Internal Combustion Engines (ICEs).
- CHP systems can reduce emissions by 35% to 50%, which is more than the current known sources of heat and power. Emissions reduction in CHP can be more than 80% when fuel cells use a low or zero-carbon source of hydrogen or biogas.
- Transit buses can demonstrate fuel economies of approximately 1.5 times greater than diesel ICEs and twice the natural gas ICE buses.
- Auxiliary power units (APUs) can emit 60% less carbon while the truck engine is idling.

Just like photovoltaic (PV) cells and electric powered vehicles, the hydrogen supply chain will face many challenges like cost, market penetration, technology advancements and availability. The pace of hydrogen utilization and its market must be in parallel with the pace of production of technological advancements. Otherwise, the hydrogen industry will not have a market, or it will have to be in parallel with the consumer market.

## 2.4.4 Replacing Natural Gas

While producing hydrogen from PV to generate energy does not sound viable, producing hydrogen from power over a long period is an efficient and stable method to store energy and provide a secure future source of power. It can even substitute natural gas and act as an energy source for many applications. The Wobbe Index is an indicator of whether natural gas can be replaced with hydrogen. The Wobbe Index considers both the physical properties of fuel gas and its heating value. The values of the Index for hydrogen and natural gas are close enough, indicating that both hydrogen gas and natural gas are interchangeable, depending on the application. Blending is an example to this replacement. According to the Australian National Hydrogen Roadmap, natural gas lines were enriched with hydrogen up to 20% by volume without the need for material upgrades or infrastructural changes (Bruce et al., 2018).

## 2.5 Types of PtX

Energy can be transformed into many useful forms. Using many methods, energy can be transformed to hydrogen (Power-to-$H_2$) depending on the source of energy. It can also be transformed into other forms of energy, such as heat (Power-to-Heat) and electricity (Power-to-Power), as well as into liquid and gaseous fuels (Power-to-Gas and Power-to-Liquid), or even chemicals (Power-to-Chemicals). In this chapter, the types of PtX will be described more thoroughly.

## 2.5.1 Power-to-Hydrogen

Both water and methane are different sources for creating hydrogen. However, water consists of 11.12% hydrogen produced by electrolysis, whereas methane gas consists of 25.13% hydrogen produced through steam reforming. This comparison is, indeed, not a key indicator, but other factors such as cost, technology availability, and environmental impact are some of many decision-making indicators.

## Methods of Production

### Electrolysis

The production of hydrogen and oxygen through water electrolysis is the most well-known technology for producing chemicals out of electricity. Passing electrical current through water will split the molecules, resulting in pure hydrogen gas and oxygen (see Figure 7). This process involves minimal impact on GHG emissions. Cost and storage issues, however, present barriers to the creation of hydrogen through electrolysis.

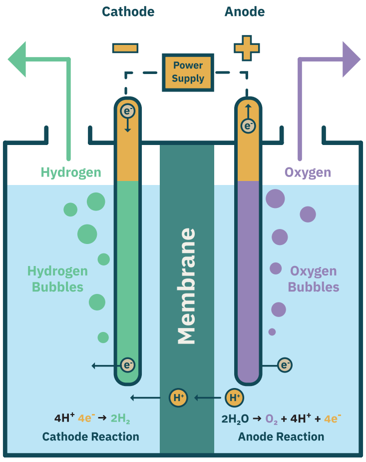



**Figure 7** Electrolysis Cell for the Production of Hydrogen Gas (Office of Energy Efficiency and Renewable Energy, n.d.)

The following reaction represents the splitting of water molecules to produce hydrogen gas and oxygen. (Water splitting is an endothermic reaction (requires energy)):

$$\text{Energy}+H_2O <\!\!-\!\!> 2H_2+O_2$$

The minimum energy needed for the reaction to produce one kilogram of hydrogen is around 40 kWh at standard temperature of 25°C and pressure of 1 (Felder & Rousseau, 2005). Using the following equation, the approximate maximum yield of hydrogen that can be produced from a certain power plant can be calculated:

$$\text{Maximum Yeild Hydrogen Gas (kg)}= \frac{\text{Power Plant Energy Production(kWh)}}{40}$$

## Steam Methane Reforming (SMR)

Another method for producing hydrogen is through SMR, as shown in Figure 8. Through this method, high-pressure steam is injected into methane gas to produce syngas, which is a mixture of hydrogen and carbon monoxide (CO). The toxic carbon monoxide is then converted to carbon dioxide (Elshout, 2010).

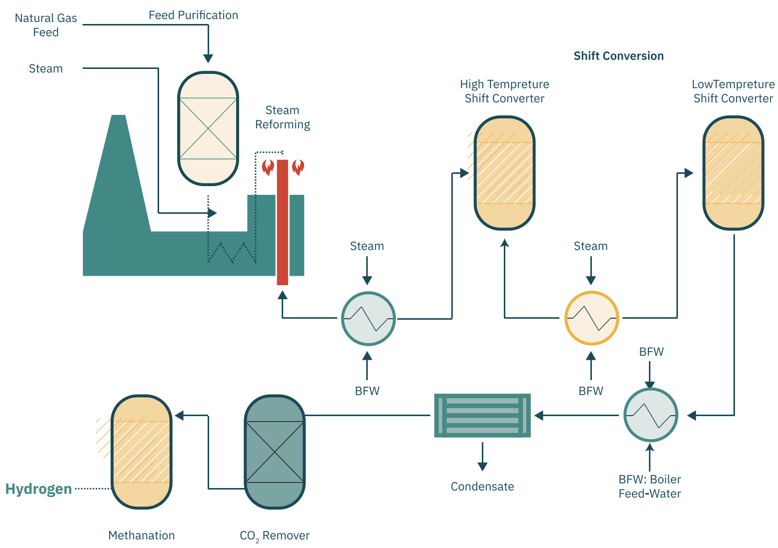



**Figure 8** Steam Reforming of Natural Gas to Produce Hydrogen (Elshout, 2010)

## Gasification

Gasification is a thermal process that converts organic material to hydrogen, CO, and $CO_2$ (Syngas) through the application of high temperatures. Such process has a well-known application in the petroleum and coal industry for generating electricity by transforming coal and heavy oils to gases. The process undergoes several stages, as shown in Figure 9. The process begins with the incineration of the feedstock, followed by a cooling stage and a final stage of gas treatment, which targets the removal of any impurities like CO, $CO_2$, and water (National Energy Technology Laboratory, n.d.).

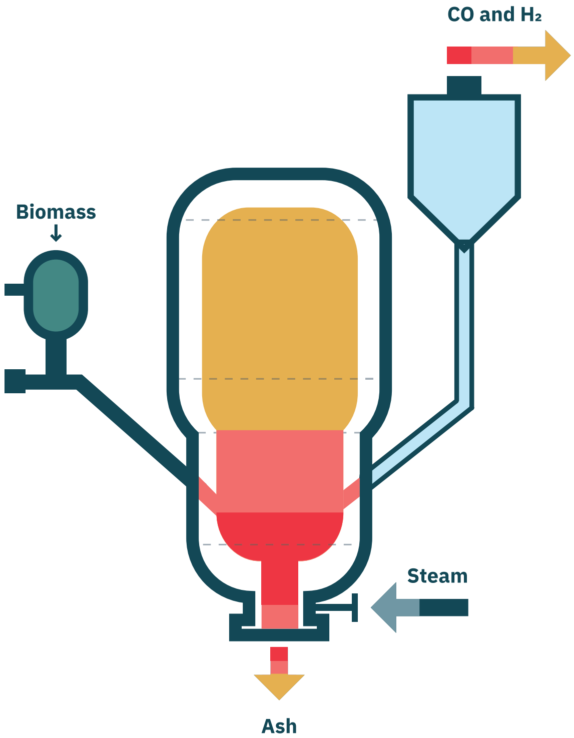



**Figure 9** Gasification Process of Biomass (Shaohua, 2009)

# 2.5.2 Power-to-Gas

When hydrogen is used in the gas line system and injected with natural gas, the infrastructure does not require major changes in the material or design (see Figure 10). Alternatively, methane can be produced through hydrogenations of $CO_2$ using hydrogen. The process involves stripping the carbon from the atmosphere and producing methane fuel.

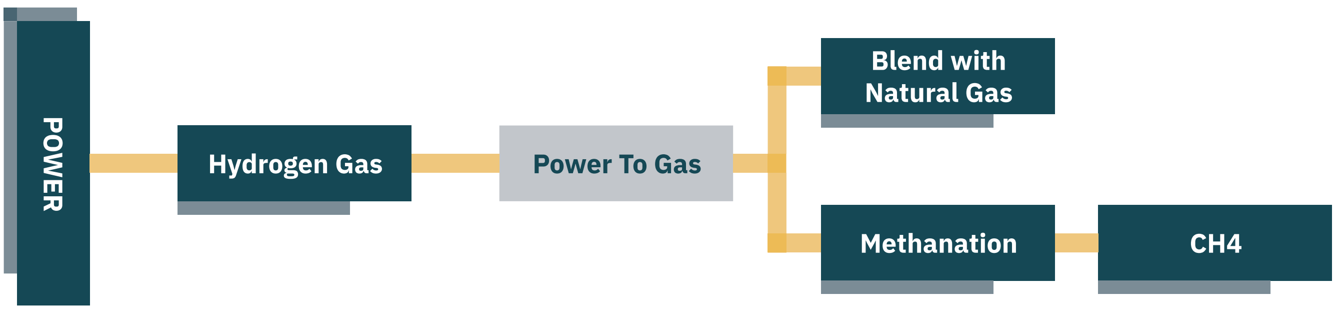



**Figure 10** Power-to-Gas

## 2.5.3 Power-to-Syngas

As shown in Figure 11, when the method of SMR or gasification of coal and solid biomass is used to produce hydrogen, CO is produced. This mixture of hydrogen and CO is called Syngas. It can be used both as a fuel and as a feedstock to create other chemicals like methanol.

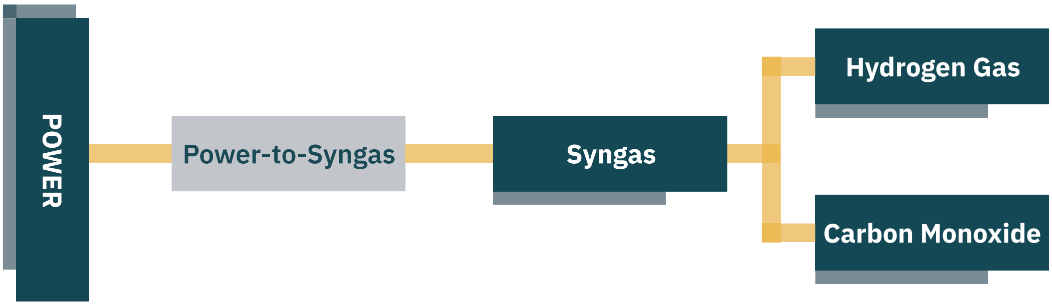



**Figure 11** Power-to-Syngas

## 2.5.4 Power-to-Chemicals

Figure 12 shows an example of power-to-chemicals whereby syngas is used to produce methanol. Methanol is a hydrogen rich liquid, which can be used to chemically store hydrogen. In fact, methanol has a wider industrial application (see Figure 13). It is commonly used as a feedstock to produce Formic-Acid ($HCO_2H$) and Formaldehyde ($H_2CO$), which are commonly used chemicals in the industry. Formic-Acid can also be produced from hydrogenation of carbon-dioxide. Another Example of Power-to-Chemicals is Ammonia production, which was explained earlier.

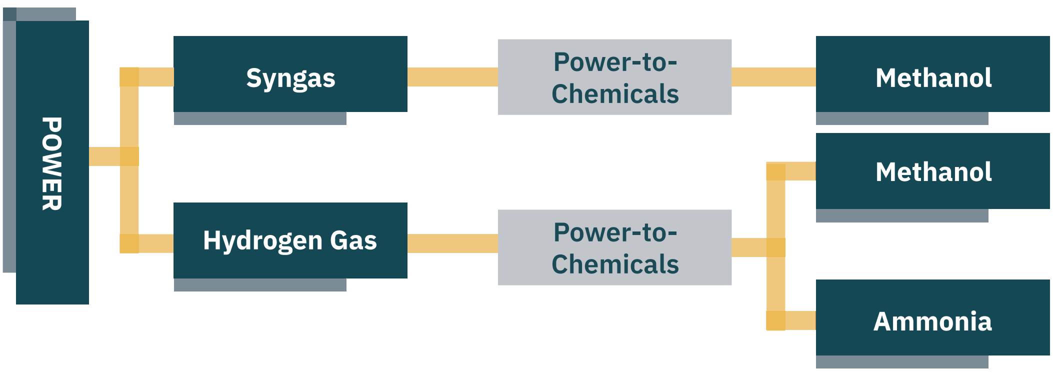



**Figure 12** Power-to-Chemicals

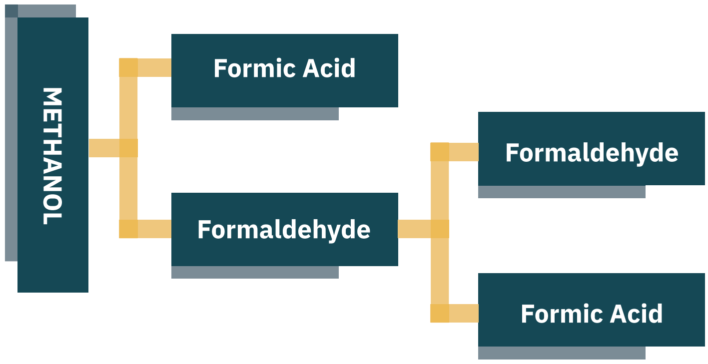



**Figure 13** Methanol-to-Chemicals

## 2.5.5 Power-to-Liquid

Methanol is also is an important feedstock for the production of olefins, dimethyl ether, and liquid fuels like jet fuel, gasoline fuel, and diesel fuel, or alkanes in general (see Figure 14). It is considered to be an appropriate energy carrier since it is stored in a liquid form. Hence, it is easier to handle and transport.

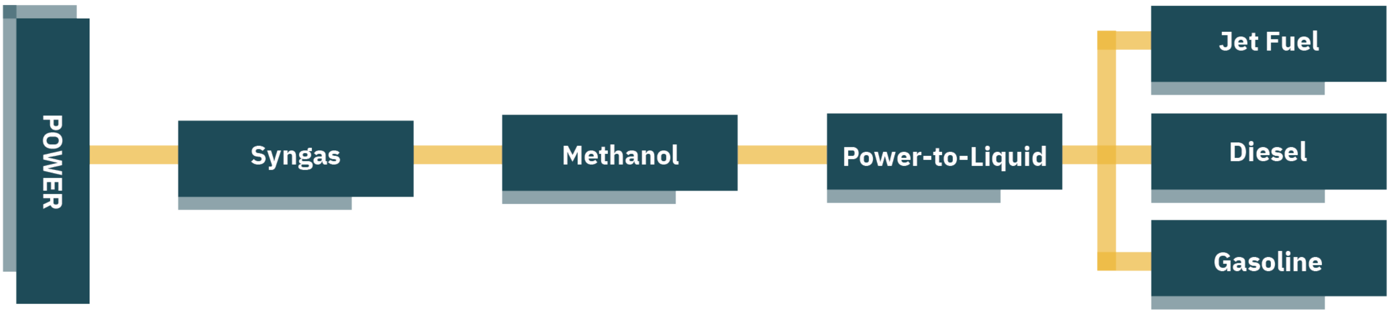



**Figure 14** Power-to-Liquid

### ■ Power-to-Power

Hydrogen can be directly used to generate electricity or power, eliminating the major source of carbon emissions of the energy and transportation sector.

### ■ Power-to-Heat

Since hydrogen has a high thermal density, it could be used as an alternative heating fuel to coal and natural gas. Heating applications may vary from buildings to industrial heating like in the hydrogen based direct reduction of iron oxide. Energy can also be directly transformed into electricity to provide heat.

# THE ROLE OF PtX IN THE ENERGY TRANSITION

## 3.1 Energy Transition Definition

Energy transition, as defined by The International Renewable Energy Agency (IRENA), is “a pathway toward transformation of the global energy sector from fossil-based to zero-carbon by the second half of this century” (IRENA, 2020). However, switching from fossil fuels to clean energy resources, such as solar, wind or water, faces many challenges. One of the greatest challenges to switch to renewable energy in the electricity sector is energy intermittency. This challenge might be overcome by using green hydrogen to manage the transition to a bigger proportion of variable renewable electricity (VRE) in the power grid. One main feature of green hydrogen is its capability of optimizing the use of renewable energy by properly integrating it with already established sectors, such as electricity, gas, and transport (Bruce et al., 2018).

To achieve a more sustainable economic system, decarbonization of the energy sector and a diverse energy mix is required. Global emissions continue to rise, despite the significant developments in renewable energy. Urgent actions should be taken to deliver cleaner energy solutions, improve energy efficiency, and accelerate investments and innovation in CCS.

The vision for the hydrogen economy in the future is to use green hydrogen as a fuel in a variety of sectors, such as industry, power generation, heat, and transportation. The aim is to avoid investments in hydrogen infrastructure by using it as raw material to produce other synthetic, carbon-neutral fuels for easier storage (Golden, 2021).
Figure 15 demonstrates roles that hydrogen can play in the decarbonization of major sectors.

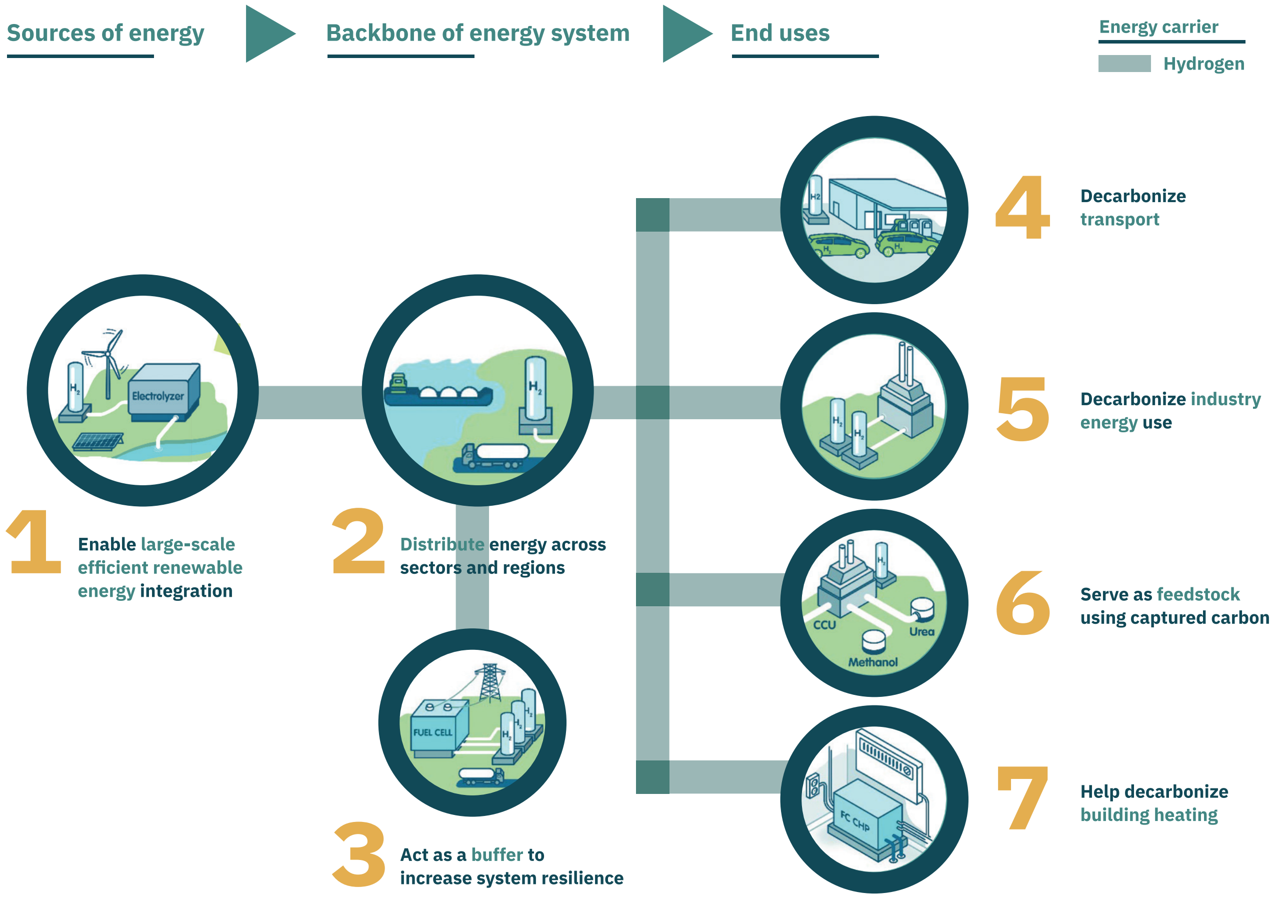



**Figure 15** The 7 Roles of Hydrogen in Decarbonizing the Major Sectors of the Economy (Hydrogen Council, 2017a)

## 3.2 Industry Sector

The industry sector is one of the biggest consumers of energy. According to the Hydrogen Council (2017b), "two-thirds of all energy is consumed by only five industries: aluminum, chemicals, petrochemicals, and refining". The Hydrogen Council (2017b) also states that cement, iron and steel, and pulp and paper need huge amounts of energy to power boilers, steam generators, and furnaces. Figure 16 demonstrates the high share of energy used in high-grade heat in heavy industries.

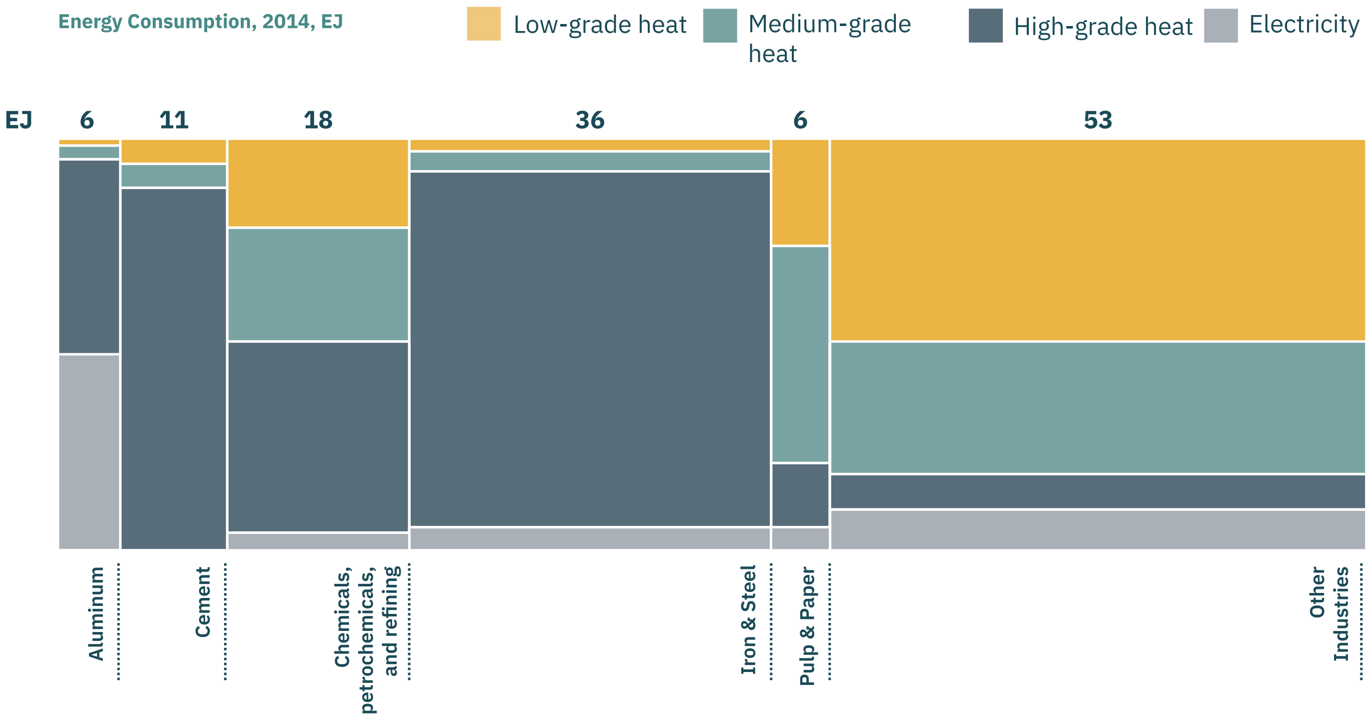



**Figure 16** High-grade Heat Constitutes a Large Share of Energy Use in Heavy Industry (Hydrogen Council, 2017b).

**Many approaches can be implemented to decarbonize the industry sector:**

-Using energy-efficient appliances and technologies and recycling materials

-Using bio-based fuels, renewable electricity, and/or hydrogen instead of fossil fuels

-Using CCS or carbon capture and utilization (CCU) (Hydrogen Council, 2017b).

Industries that are energy-intensive and that embrace hydrogen as an alternative will contribute to pushing this sector toward achieving the national and global $CO_2$ reduction targets. Hydrogen could be utilized for decarbonization in different industries, such as the iron and steel industry, the chemical industry, aluminum recycling, and refining.

Hydrogen from renewable power can be used to displace fossil fuels in end-use sectors. This would result in turning those industries fully green. To achieve this goal, many applications must be executed, such as substituting natural gas and other fossil fuels with hydrogen to obtain high-grade heat (>650°C). This is done through the combustion of hydrogen in specialized hydrogen burners.

Another application, blast furnaces for ironmaking, uses coke to create heat and melt iron. This process enables a chemical reaction between the oxygen in the iron ore and carbon electrodes in the coke to decrease the ore to iron. In this case, the equipment could be retrofitted using hydrogen (or using hydrogen or a combination of hydrogen and other combustible fuels) to enhance the heat of the blast furnace (Hydrogen Council, 2017b).

## 3.3 Transport Sector

The transportation sector is another sector that depends almost entirely on fossil fuels. It is a major contributor to GHGs since it emits more than 20% of all $CO_2$ emissions, and this amount is expected to increase in the upcoming years. Both the European Union (EU) and the United States (US) are targeting this sector for decarbonization with hydrogen in the mid-2020s, whereas India and China will target it in the mid-2030s. The Hydrogen Council (2017b) estimates that the introduction of 80 million zero-emission and 80 million plug-in hybrid electric vehicles (PHEVs) will achieve the two-degree scenario in 2030. This would "require a wide range of technologies" (Hydrogen Council, 2017b).

The transportation sector (including all segments from motor scooters to ocean-faring container ships) is determined by two metrics: range and payload. The performance needed from both the engine and storage is contingent upon those metrics, and all the segments currently depend largely on fossil fuels (Hydrogen Council, 2017b). Therefore, "hydrogen and fuel cells are critical elements in the decarbonization of the transportation sector" (Hydrogen Council, 2017b). However, the degree of difficulty in decarbonizing transport varies across the segments.

The Fuel Cell Electric Vehicles (FCEVs) will play an essential role in decarbonizing the transport sector, according to the Hydrogen Council (2017b). The Council expects that FCEV passenger cars could represent almost 3% of new vehicle sales in 2030 for 4 million vehicles as total sales. The figure is expected to increase up to 35% in 2050. It is expected that Germany, Japan, California, and South Korea would lead the global markets in FCEV adaptation (Hydrogen Council, 2017b).

According to the Hydrogen Council (2017b), interest in fuel cell buses has also been increasing due to local pollution problems, especially in Europe, Japan, South Korea, and China. On the one hand, smaller buses and buses with short-range requirements will operate on batteries. On the other hand, larger buses will operate on fuel cells, allowing them to travel longer distances and with fewer interruptions. The infrastructure issue is less of a concern for buses, which rely on purpose-built refueling facilities.
In addition to the FCEVs, hydrogen may play a role as feedstock for synthetic fuel in freight shipping and aviation. These fuels have similar properties to conventional fossil fuels that produce energy by combustion in engines.

Those synthetic fuels that incorporate the use of $CO_2$ and hydrogen create a closed carbon cycle. Thus, this method is a valuable option to decarbonize combustion engines. It is more likely for synthetic fuels to be used by 2050 because of the efficiency losses during the process (Hydrogen Council, 2017b).

## 3.4 Heat for Buildings

In terms of heat building, 80% of the residential energy is being consumed for heating and supplying warm water. Hydrogen can contribute to reducing this consumption and decarbonizing building heating. It can be used as a fuel "either pure or blended with gas, partially decarbonizing the gas grid" (Hydrogen Council, 2017a). Hydrogen technologies, such as fuel cell micro-CHPs, can be employed as energy converters. These technologies offer high efficiency of more than 90% for heat and power generation. Moreover, there is an opportunity to switch houses connected to the natural gas grid to hydrogen-combustion-based heating using the existing gas grid (Hydrogen Council, 2017a). "With relatively small adjustments and investments, the grid can safely transport a mixture of hydrogen and natural gas" (Hydrogen Council, 2017a).

A project in Japan already used hydrogen-based fuel cell micro-CHPs to heat 190,000 buildings. The project demonstrated the capability of micro-CHPs in meeting the heating requirements and supporting the electricity balance. It is estimated that 5.3 million Japanese households will use micro-CHPs by 2030 (Hydrogen Council, 2017a).

## 3.5 Feedstock

According to the Hydrogen Council (2017a), "hydrogen-based chemistry could serve as a carbon sink and complement or decarbonize parts of the petrochemical value chain". Nowadays, industrial chemicals, fuels, plastics, and pharmaceutical goods use crude oil (derivatives) as feedstock in the process of their production. The majority of these products possess carbon as well as hydrogen. The Hydrogen Council (2017a) mentions that "if the application of CCU takes off (as part of a circular economy or an alternative to carbon storage), the technology will need (green) hydrogen to convert the captured carbon into usable chemicals like formic acid, methane, methanol, or urea. This use of hydrogen would make CCU a viable alternative for other hard-to-decarbonize sectors like cement and steel production, and would contribute to the decarbonization of part of the petrochemical value chain".

The Hydrogen Council (2017a) also states that using hydrogen and CCU to create chemical feedstock is currently in the research and development (R&D) stage, and initial pilot projects are starting. In Iceland, there is an operational geothermal plant that produces hydrogen and methanol using geothermal $CO_2$ and generated electricity. This method of methanol production is predicted to be cost-competitive, with a projected electricity price of EUR 30/MWh (Hydrogen Council, 2017a).

# JORDAN - ENERGY SECTOR AND UTILIZATION OF HYDROGEN

## 4.1 Energy Status of Jordan

Jordan's main challenge is securing energy, seeing as the country suffers from the scarcity of natural resources, as well as regional instability and conflicts. As shown in Figure 17, Jordan's energy mix between 1990 and 2018 was dominated by fossil fuels (oil and natural gas). There is an opportunity to integrate renewable energy in the energy mix as a local source, but it will be difficult to achieve this goal. Moreover, Jordan imports around 91% of its energy supply. Hence, it urgently needs to move towards using green hydrogen in order to decrease its imported fossil fuel dependency and increase the penetration of the locally sourced renewable energy.

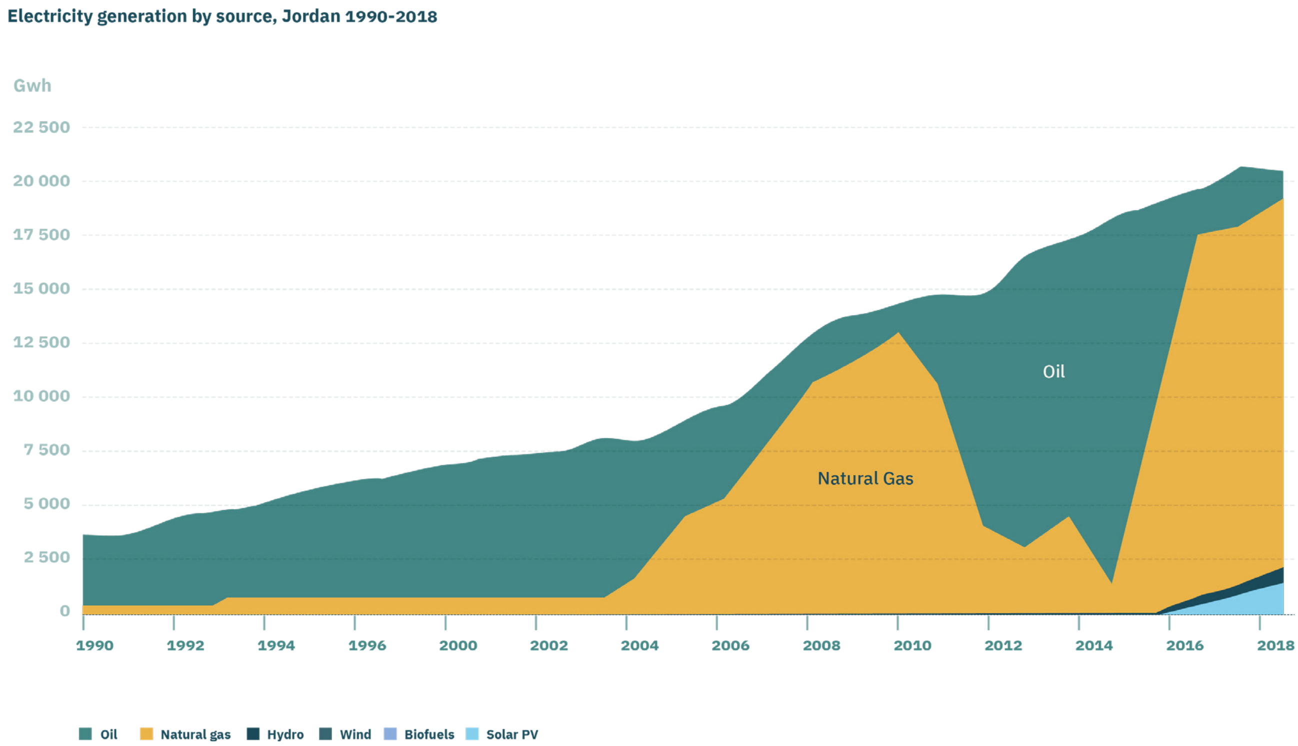



**Figure 17** Energy Generation in Jordan by Source (IEA, 2019)

As depicted in Figure 18, the electricity and heat producer sectors were the largest contributors to $CO_2$ emissions in Jordan in 2018, which is almost double the amount in the transportation sector. As Figure 17 illustrates, oil and natural gas were the most used resources in electricity generation, with natural gas being utilized more in 2018. Knowing this data is essential for reaching Jordan's target to reduce GHG emissions by 14% until 2030.

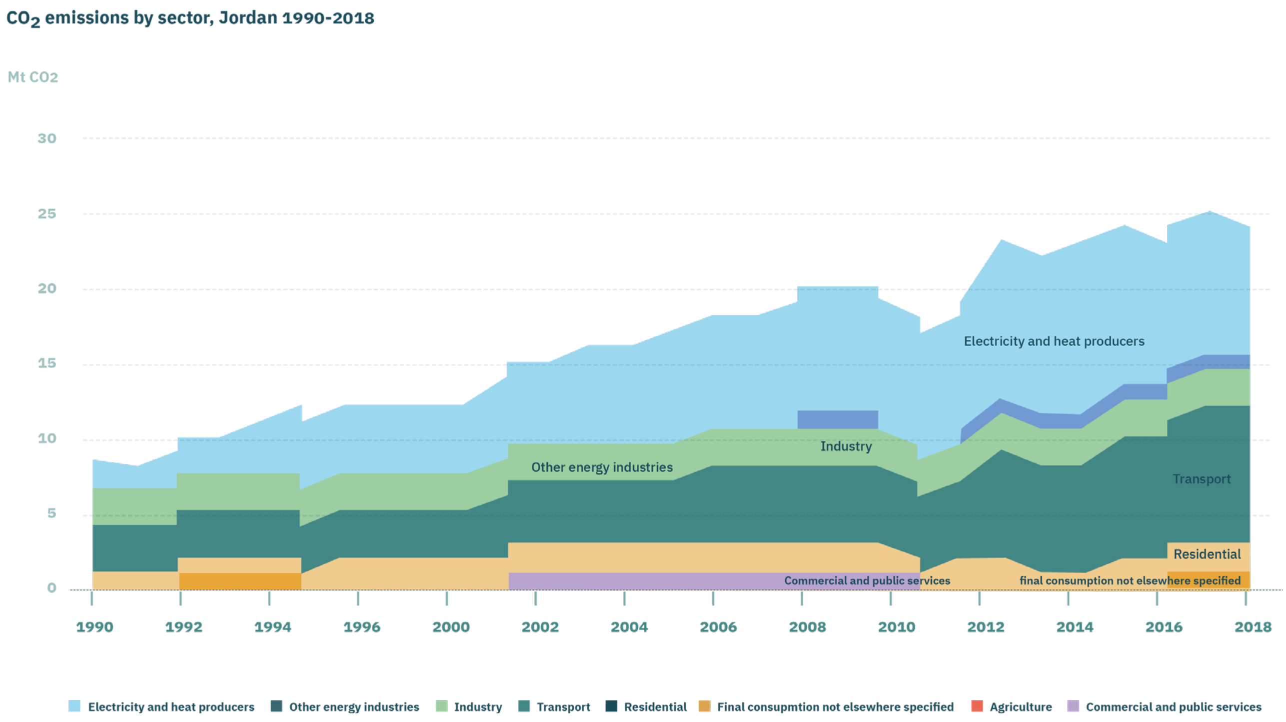



**Figure 18** $CO_2$ Emissions in Jordan over the Years by Sector (IEA, 2019)

On July 7, 2020, the Ministry of Energy and Mineral Resources (MEMR) released the 2020-2030 Energy Strategy. MEMR aims to diversify the energy resources, expand the utilization of renewable energy sources, increase the investments in mineral resources, and endorse international relations and collaborations. MEMR also intends to reduce the cost of electricity and involve the local energy producers in Jordan's energy blend. Moreover, improving energy efficiency by strengthening national energy efficiency legislation and implementation of plans is one of the primary objectives of the strategy. On a more national level, MEMR aims to enhance the services provided to the society with equal distribution, and it attempts to encourage foreign and local investments in Jordan (MEMR, 2020).

## 4.2 Renewable Energy Utilization in Jordan

In 2020, 80% of the electricity in Jordan was generated from natural gas, whereas the remaining 20% was generated from renewable energy (see Figure 19). In the same year, there were 30 renewable energy companies that generated electricity, 7 of which through wind energy, 22 through solar energy, and 1 through bioenergy (MEMR). Between 2015 and 2020, Jordan increased renewable energy's contribution to the energy mix from 2% to 11%, which was a great achievement (Abu-Dayyeh, 2020).

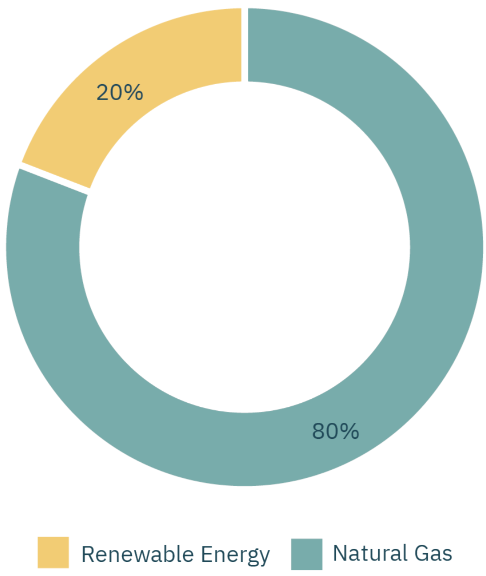



**Figure 19** Electricity Production Percentage by Source

The 2020-2030 Energy Strategy plans to increase renewable energy's share of the entire energy mix from 11% in 2020 to 14% by 2030. The strategy also calls for a reduction in electricity generation from natural gas to reach 53% in 2030, and it aims to increase renewable energy to 31% (MEMR, 2020). This accounts for only 84% of the total electricity generation, leaving 16% as a potential for other sources, such as oil shale, to enter the market.

## 4.3 Green Hydrogen Main Streams for Market Penetration

It is essential to understand that for green hydrogen to have a market space, many steps must be taken beforehand. There are many factors that can enable hydrogen to penetrate the market, which can be divided into several main streams in the supply chain from the supplier or producer to the end user.

### Production and Import

The sourcing of green hydrogen is either through production or through imports. However, these methods face several barriers, which include the lack of technology, insufficient R&D, and the lack of policies that support the production and import of green hydrogen. As a result, the production has  high capital expenditures (CAPEX) and operational expenditures (OPEX), leaving the market stranded with few sources and high competition.

Production of green hydrogen in Jordan should be regarded as a great business opportunity. The favorable sun conditions and previous record-breaking prices of renewable energy can attract international businesses to produce price-competitive green hydrogen. The government can support the producers by facilitating financing, and it can secure a sustained market with stable and clear supporting policies. To reduce the risk for producers, a collaboration between the private and public sector should be formed, and a clear national green hydrogen strategy should be established. Moreover, joint efforts with international partners as well as subsidies and incentives given by the government would divide the risk, allowing producers to learn together and make fewer mistakes. Thus, costs are reduced and advancements are accelerated. The clear government strategy should serve as a reference to the private sectors when developing targets for the green hydrogen industry, and it should help attract financing.

Policy making must be made for the most valuable applications, and the strategy should consider not only energy policies but also climate, transportation, and industrial policies. All of this enables the commercialization of green hydrogen through creating a market place and reducing costs. A long-term contract with the private sectors can be very important in bringing security for investors and makes the market more approachable. This allows the producers to scale up their operations, and, in turn, close the cost gap.

It is noteworthy to mention that the process of encouraging the private sector to invest in green hydrogen should not affect Jordan's own resources negatively. Jordan has been successful in deploying renewable energy as part of the national energy mix, and this renewable energy share now belongs to the people of Jordan, and it is not to be used to power the green hydrogen production facility. If a facility is to be built, then a dedicated renewable energy project should be built with it.

## Production and Export

The international hydrogen market is expected to be more mature than the national one in the years to come. Countries and regions have already introduced their green hydrogen strategies and visions. Therefore, potential off-takers are accumulating overseas, which will revive a business case for green hydrogen production in Jordan. This green hydrogen would then be exported to ready markets, if the conditions are right. And with an existing green hydrogen facility, the in-house use of hydrogen can become much more feasible and attainable, especially since the hydrogen facility is built and operated by the private sector, removing much of the risks.

## Transportation and Storage

Hydrogen must be taken one step further to the end-user or the next market. While the R&D sectors and the policies are set to focus on production, it is important to concentrate on transportation and storage of hydrogen as well. Infrastructure is very essential to attract local and international producers and reduce the cost of logistics, which eventually leads to a lower hydrogen cost and encourages local and non-local investors. The technology of storage and transportation is still being developed to meet the market's expectations. The potential of using hydrogen in the transport sector is huge, particularly in the heavy-duty vehicle market segment. However, this deployment requires greater policy intervention.

## Utilization of Hydrogen

Hydrogen can be utilized in many ways, and the end user is at the end of the hydrogen supply chain. This segment consists of the transformative PtX industries, retail, wholesalers, exports and transportation (commercial and non-commercial). These fields are mostly yet to be developed on a commercial scale, and the most important enabler is the government, which could cut down cost and create a market. In many ways, the government can create policies that motivate all the stakeholders to participate in the transformation.
The government could assume previous trends and follow measures that were considered in the past, while introducing new and renewable energy to the market. Otherwise, it can start by adopting enabling policies and measures for the creation of a socioeconomic space that would allow green hydrogen to become part of the energy

system. A scheme should be developed that provides clear certification for hydrogen and hydrogen products to increase awareness among customers, and it should also differentiate between green hydrogen and hydrogen produced from fossil fuel or coal (Bianco & Blanco, 2020). It is important as well to consider the principle of additionality, which means that should there be energy from a renewable source that could be utilized in any productive mean, this energy should not be diverted to green hydrogen (Bianco & Blanco, 2020). To ease and drive the transition of industries from fossil fuel, a fuel blend mandate including hydrogen addition could be a huge driver for a transition.

## ■ Putting a Price on Carbon

Carbon emissions have high environmental and health impacts. Thus, it is important to fix a price on carbon or make carbon taxation by charging enterprises for their carbon emissions. This could act as a motive to switch to renewables, and it can give green hydrogen a higher potential in the market.

## ■ Job Creation

Jordan's renewable energy market is one of the biggest in the region. The business boom that happened in the previous six years attracted so many engineers, skilled workers, and other professionals. More students have chosen to study this field and are expected to join this sector's workforce in the future. However, the limitation on Jordan's electrical grid is forcing the renewable energy market to shrink in the upcoming years, which implies a reduction in the number of projects and a decline in the demand for jobs. In fact, people from the sector have already lost their jobs.

Green hydrogen facilities require a great deal of renewable energy. Only one facility can require as much as Jordan's entire electrical system capacity. Large-scale renewable energy projects can provide hundreds of jobs, ensuring the continuity of this sector, not to mention the indirect jobs that would result from such a project, especially for logistical services providers.

## ■ Points of Focus

Within that scope, it is important to find the applications that have the highest value and prioritize actions accordingly. The production of hydrogen should put the concept of additionality into consideration. Where the renewable electricity of green hydrogen production should not be diverted from more immediate and efficient direct uses, and where the use of hydrogen is sustainable. Application must imply with Jordan's national plan, and bringing focus on potential industries like green ammonia, or power-to-liquid that can and in the present time supplying jet fuel that is operational (IRENA, 2020).

# PtX CHALLENGES IN JORDAN (FOCUSED ON GREEN HYDROGEN)

## 5.1 Infrastructure

Hydrogen needs to be transported, and various forms of infrastructure will be required to transport and store either green hydrogen or hydrogen-based synthetic fuels. There are different ways to transport hydrogen, depending on the hydrogen form. If the hydrogen is pressurized, then it can be transported through pipelines. The gas pipeline in Jordan is the network of the Arab Gas Pipeline that currently connects Jordan to Egypt. There are plans to spread this network across the Levant in the future. This network is still recovering from attacks and unstable political situations around Jordan, and there are already concrete plans to use it for natural gas. Hence, introducing hydrogen to it requires a lot of effort and planning.

Another way to transport hydrogen would be through ships. It must be liquefied or converted to ammonia or liquid organic hydrogen carriers (LOHC) for greater energy content by volume. Any additional conversions require energy consumption for liquefaction and continuous cooling. Aqaba port's readiness and needed infrastructure must be studied carefully by any business that wishes to produce hydrogen in Jordan and export it overseas.

Network infrastructure is the main difference between natural gas and hydrogen markets. Without an underlying physical market servicing an established supply/demand infrastructure, it will be hard to contemplate a traded hydrogen market. New infrastructure, such as pipelines, ports, storage, hydrogen-ready engines and gas turbines, and hydrogen cars, is required. As a start, it could be possible to blend between hydrogen and existing natural gas infrastructure or use it on-site. However, designing and implementing this project will be time consuming.

Many projects in Europe are focusing on adopting the green hydrogen infrastructure. For instance, the European Hydrogen Backbone (EHB) is a new important pipeline infrastructure formed by 11 European Transmission System Operators (TSOs). They published their first report in July 2020 and added 23 other TSOs from 21 countries. In April 2021, they published an updated report that consists of further details of the network plan and cost analysis (Barnes et al., 2021). By 2030, the EHB will connect emerging hydrogen clusters with an initial pipeline network of 11,600 km (Barnes et al., 2021). Another example is the port of Rotterdam and its plan to become an international hub for hydrogen production, import, application, and transport to other countries in Northwest Europe (Port of Rotterdam Authority, n.d.). The Port Authority and the gas network operator Gasunie are working on an initiative to have a pipeline for hydrogen running through the port as early as 2023. This main transport pipeline will supply companies with hydrogen produced at conversion parks in the port. The backbone will be connected to Gasunie's national infrastructure throughout the Netherlands and to corridors leading to industrial areas in Chemelot in

Limburg and North Rhine-Westphalia. There are also plans to develop a terminal to facilitate imports of hydrogen. The above strategy by the EHB shows the importance of cooperation between EU countries in developing hydrogen infrastructure with neighboring countries. Jordan should develop a plan to strengthen national transmission and distribution infrastructure, seeing as the infrastructure is considered a key hurdle. Priorities should be identified by the government of Jordan, and investments must be mobilized towards building hydrogen infrastructure.

## 5.2 Water Scarcity

In 2019, Jordan was recorded to be the fourth most water-scarce country in the world (Dormido, 2019), with rainfall ranging from 30-600 mm/year. More than 80% of the land area is desert and receives less than 100 mm/year; only 4% receives more than 300 mm/year. Apart from relying on precipitation, Jordan also receives water from international rivers, such as the Yarmouk River. Water withdrawals by other riparian countries mean that only limited amounts are available for Jordan. Climate change further increases the challenge by decreasing the amount of water available to Jordan. As a consequence, Jordan faces severe water scarcity.

Using water as a feedstock for developing molecular hydrogen as a fuel and energy storage medium is, therefore, one of the main challenges. The production of grey and blue hydrogen requires an ample amount of water for steam in the reformation process. Hydrogen production via electrolysis requires water as well as one of the major inputs. To create 1 kg of hydrogen, 9 liters of high purity water is required. The high purity water is used to limit side reactions caused by ions (salts) found in naturally occurring water (National Energy and Action Plan, 2015).

Nevertheless, it would still be possible to source water for a green hydrogen facility in Jordan through water desalination from the red sea through Aqaba, but only if it does not compromise Jordan's water security. Yet, validation of this approach must be done through different feasibility studies and proper coordination between stakeholders.

## 5.3 Regulatory Framework

Analyzing the prospect future of traded green hydrogen market cannot be achieved without a political and regulatory framework. It is the most essential element to consider. Those frameworks should directly or indirectly promote hydrogen use across various end-uses, support the market, and create the proper environment to attract market participants.

Although green hydrogen and grey hydrogen are the same gas, tracking the origin is essential to apply the right incentives and policies. To make policies that would enable the market, applications with the most values should be the focal point. That includes a forecast for the market profile for the coming decades. Alongside the enabling policies, the market itself should also enable proper partnerships, infrastructure, financing, and research.
The government should provide a secure and supportive policy to facilitate adequate private investment across the whole hydrogen supply chain network. For instance, it should offer equipment manufacturers, infrastructure providers, and vehicle manufacturers. The time required for replacing vehicle fleet and range of demand to reach the costs reduction for new technologies will be part of the challenge. The government can also offer incentives, such as tax rebates and a simple phase-out plan.

## 5.4 Cost (CAPEX & OPEX)

Cost is a barrier to enabling the hydrogen market in Jordan. This hurdle is associated with the aforementioned challenges. If hydrogen was cost-competitive with conventional fossil fuels, it would have already been employed. One of the main challenges in this regard is the cost associated with generating green hydrogen, which produces $H_2$ with near-zero or low carbon emissions. However, current $H_2$ production utilizes the combustion of fossil fuel-based feeds (such as coal and natural gas) that generate high amounts of $CO_2$. The cost of producing green hydrogen is relatively high (2 to 3 times) compared to the cost of producing grey hydrogen. The cost of green hydrogen also depends on the investment cost of the electrolysis system, their capacity factors, and cost of producing electricity from renewable energy resources.

Yet, after the global drop in price for solar energy, it is also expected that the prices of hydrogen will eventually drop. This is normal, as the economy of hydrogen would change with time due to the economy of scale, the increasing demand, and technological advancements that make the technology cheaper.

Jordan can also learn from the already existing efforts in Morocco for establishing a green hydrogen economy, for Morocco and Jordan share a lot of similarities in terms of their energy profile and the mutual interests between them and Europe. Information on the Moroccan experience can be found in Annex I.

# RECOMMENDATIONS FOR PtX IMPLEMENTATION IN JORDAN

The analysis in the previous chapters demonstrated how green hydrogen could play a vital role in global decarbonization for many sectors, such as the energy, industrial, and transportation sectors. The analysis showed that hydrogen can be used for many applications. However, careful attention to policy is required to meet the challenges mentioned in chapter 5. The green hydrogen economy will not only stimulate economic growth, but it will also offer the potential to create new jobs in this sector. The following points could be considered for policy makers and researchers:

## 6.1 Setting Priorities

In order to enable and assure an easy entry of green hydrogen to the market, it is essential to prioritize the sectors that are easier for green hydrogen to penetrate and where it can be effective in reducing the country's $CO_2$ emissions. **This could be accomplished by considering the following factors:**

- Decarbonization of hard to abate sectors like the iron, steel and cement industries
- Sectors that are impacting Jordan's environment the most must be the top priorities. This is shown in Figure 18 in $CO_2$ emissions measured by sector.
- Energy intensive sectors are important to consider, especially with Jordan's plans to reduce the use of natural gas in electrical generations and with hydrogen being a great energy carrier (see Figure 20).
- Technological advancements in transportation are unlike those in ammonia production. Thus, it is easier to penetrate a market that has the technological and research tools than one without due to cheaper production and more economical feasibility. A different study and benchmarking should be conducted to investigate those aspects.

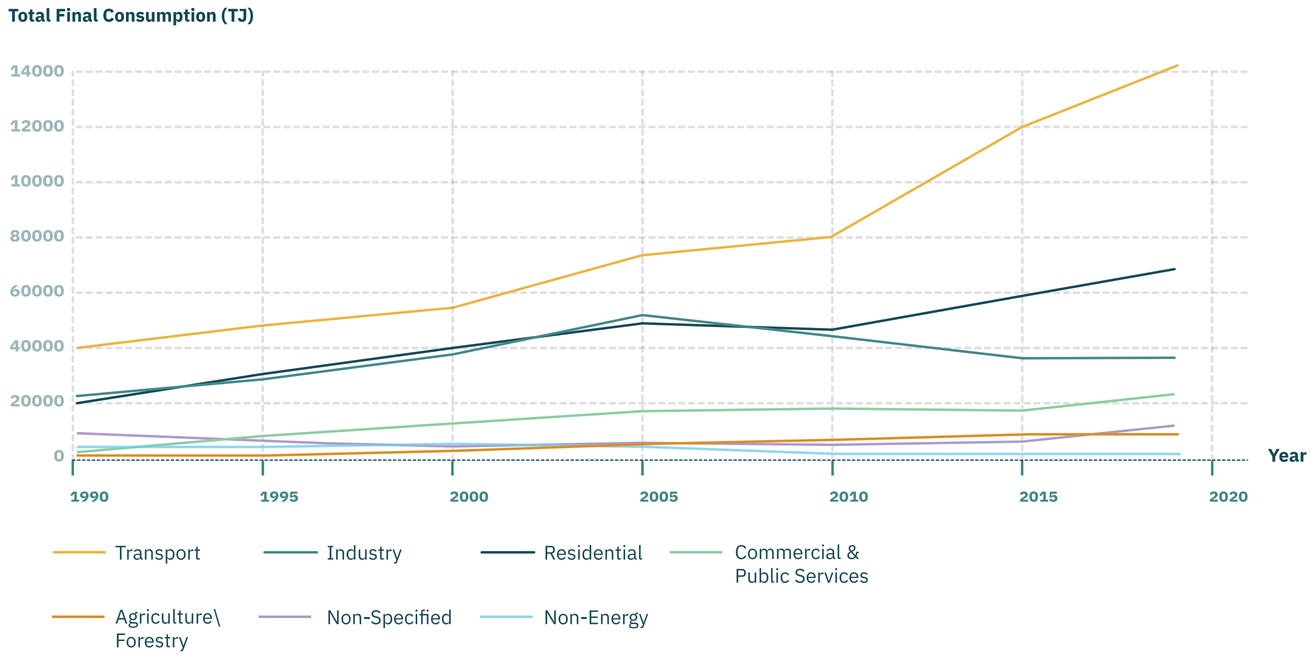



**Figure 20** Total Final Energy Consumption in Jordan (By Sector) (IEA, 2019)

Setting sectors of focus can attract investors and focus funds on important economic activities, hence enabling hydrogen to enter the market through some activities while other markets are being developed.

## 6.2 Roadmap and Policy Framework

Green hydrogen must be added to Jordan's 2020 - 2030 Energy Strategy to act as a foundation for the introduction of other policies and to attract foreign investments and development cooperation. Afterwards, a strategic roadmap for hydrogen and fuel cells should be developed. The roadmap should include hydrogen use in industry, hydrogen supply chain, and mobility. A supportive and stable policy framework should be included to encourage the appropriate private investments, overcome the initial resistance, and reach a minimum threshold or market penetration. In the mobility sector, only the policy framework will allow the FCEVs technology to compete with other technologies like hybrid cars and EVs. The framework will also assist in reducing costs in filling stations, storage, and transportation. The framework will reduce the overall cost and increase the choices for the end-users. The policies should facilitate financing the development of hydrogen infrastructure, and funds from the public and private sectors might be needed to achieve significant network expansion.

## 6.3 Incentives

Incentives can be provided in different forms. In the transport sector, direct subsidies, taxation, and discounts could be applied to stimulate FCEVs. For instance, the Jordanian government exempted EV from taxes and customs duties between 2015 and 2019. As a result, the use of EV cars increased during this period.

In the industrial sector, investment subsidies or loans could attract investments. The Energy and Climate Fund in Germany allocated EUR 45 million to help decarbonize industries, such as the steel, cement, and chemical industries, and support the hydrogen path by 2024.

## 6.4 Pilot Projects

Strategic pilot projects are likely to be a significant part of any new technology's development, such as with FCEVs, in this case. Providing the initial infrastructure as well as demonstrating the usefulness and safety of FCEV technologies will aid in managing risks with minimal investments. This will also lead to gaining further experience in real-life situations with technological, economic, and regulatory variables. In the long term, pilot projects will help in creating codes and standards according to the acquired results. Pilot projects will also contribute to educating the public on the use and benefits of hydrogen.

## 6.5 Creation of a Green Hydrogen Steering Committee

Under the coordination of MEMR, members of a committee consisting of policymakers as well as research and governmental entities and the private sector, could potentially become stakeholders in the emerging green hydrogen market and its associated industries. The committee could drive the market by making feasibility studies, shedding light on the environmental and social impacts of utilizing green hydrogen in Jordan, and advising the government on all matters related to green hydrogen. In addition, the committee could act as a contact for international hydrogen stakeholders, such as companies, energy partnerships, or hydrogen steering committees from other countries, which would be the basis for bilateral or multilateral collaboration with other countries and entities.

## 6.6 Collaboration with Neighboring Countries

As mentioned previously, agreements and cooperation are needed between Jordan and neighboring countries to facilitate trading across borders. The infrastructure is currently limited, but the agreements should include piloting routes and carriers, operational safety standards, and pipeline integrity requirements to assure the sustainability of the supply chain over time. Initiating government-level agreements between Jordan and other countries will help in building hydrogen supply networks and reducing costs associated with transportation and storing hydrogen.

## 6.7 Using Electrolyzers to Increase Electricity Demand

A green hydrogen facility requires renewable energy to provide electricity to the electrolyzers in order to produce hydrogen. In Jordan's case, the renewable energy source is going to be solar PV, which can only generate electricity during the day. This means that the electrolyzers will not be operating at night. If these electrolyzers are supplied by electricity from the national grid for a certain tariff, then they will work as on-demand load control with a very high consumption ability. Electrolyzers can benefit the hydrogen facility operator by producing non-green hydrogen at a favorable price for export or local use. They can also benefit the Jordanian electrical grid by using power generators that are otherwise wasted.

This can be important to support the financial model of the National Electric Power Company (NEPCO), as there is an issue of overcapacity of generation in Jordan, causing some power plants to stay idle while capacity charges are being paid for. Thus, it would be better if the power plants are utilized and paid to generate electricity rather than being paid with no return.

## 6.8 Desalination Plant in Aqaba City

To produce green hydrogen whether for export or local use, the most important issue to resolve is sourcing the water. It is important to source water without affecting the share for the Jordanian people. One method to achieve this is to build a water desalination plant in Aqaba, by the Red Sea, specifically for the hydrogen production facility. This water desalination plant in Aqaba should be supplied by renewable energy only to keep the energy along the process green. A detailed feasibility study should be conducted taking into consideration all factors in order to plan for such a project.

If a water desalination plant is to be constructed by the hydrogen facility operator, then it is possible to enforce a certain water output for Jordan's national use.

## 6.9 R&D Investment

R&D are very essential for the growth of hydrogen and the expansion of the supply chain. Support for R&D should be considered to improve the efficiency of electrolysis systems and to standardize designs for large-scale electrolysis systems. Such research may lead to breakthroughs in the technology and reduce costs of hydrogen for end users.

A research facility could be designed and equipped in Jordan with all needed tools in order to enable interactions between scholars and industry. The research facility in this area will enhance research opportunities and knowledge creation. It will also solve problems relevant to the green hydrogen technology. The research center could play a vital role in promoting and disseminating knowledge.

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# Annex I: Country Example: Green Hydrogen Economy Deployment in Morocco: Strategy and Ongoing Advances

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## 7.1 Energy Transition in Morocco

Since 2009, Morocco has been engaged in an ambitious energy transition, targeting 52% installed capacity out of renewables by 2030. Today, the country has a total green power capacity of around 3.95 GW (1.77 GW hydro, 1.43 GW wind, and 0.75 GW solar), which is approximately 38% of the total installed capacity. The country is, therefore, a leading example for countries in Africa as well as in the Middle East and North Africa (MENA) region.

The country has also demonstrated its capacity and leadership in implementing ambitious renewable large-scale plants through the incorporation of innovative technologies. This is the case with the NOOR projects that showcased the Concentrated Solar Power (CSP) technology in Ouarzazate, featuring some world records in terms of scale (size of the turbine, solar field, height of the solar tower).

This endeavor has resulted, over the decade, in substantial achievements, paving the way towards a successful energy transition. For instance, Morocco has succeeded in lowering its dependency on fossil imports by 7 points (from 97.5% in 2009 to 90.5% in 2020), which (besides the environmental impact) helps in strengthening the country's economics and international commerce balance. In addition, this renewable dynamic has generated a total investment effort of about USD 6 billion through nearly 50 projects and the establishment of 30+ companies from 12 different countries.

Looking at a post-coronavirus disease 2019 (COVID-19) decade, the country is about to take its energy transition to a higher level, targeting a deep decarbonization of its economy and exports. Indeed, the EU, one of the major partners of Morocco, will progressively settle carbon taxes at its frontiers by 2023 and 2025. This will concern approximately, among others, USD 10 to USD 15 billion-worth of exports (mainly in the car and aviation industries). Therefore, the country will reinforce its sustainability strategic plans in terms of renewables, energy efficiency, e-mobility, as well as the production, export, and use of high added value green molecules, such as hydrogen. In this regard, Morocco is undertaking a large study on e-mobility to lower its GHG emissions in the transport sector, while creating local value, jobs, and exports. Moreover, the country has recently published its Green Hydrogen Strategy, as a pioneer in green hydrogen in the MENA region, confirming its sustainability leadership and strong will.

## 7.2 Green Hydrogen in Morocco: Vision and Strategy

Discussions on Green Hydrogen in Morocco were initiated at the end of 2017 through the Moroccan-German Energy Partnership (PAREMA). In 2018, two preliminary studies were launched to assess the technical potential, economic opportunities, markets, as well as technologies relative to this industry. It has been stated that the country could reach up to 4% of the global PtX market by 2050. In a study published in 2018 by the World Energy Council, Morocco was identified as a front runner country concerning its PtX economy with a "hyped potential" of both wind and solar, enabling a very competitive production of green hydrogen and other high-added value green molecules. In 2019, a third, more detailed study was launched in order to define the outline of a Moroccan Green Hydrogen Strategy, which was published in August 2021.

**The strategy outlines 3 main working axes to deploy a hydrogen economy in general:**

- Scaling up Technologies,
- Stimulating Market and Demand
- Enhancing Investment and Supply

As per Morocco, short-term opportunities have been identified as the **export market**, mainly in the EU. A **niche domestic market** of ammonia-based fertilizers, one of the leading industries in the country, has also been identified. Indeed, the Moroccan fertilizers industry imports around 2 million tons per year of ammonia. Therefore, domestic production of green (and competitive) ammonia could help decarbonize the phosphate industry of the country, while creating industrial value and reducing import dependance. Besides, ammonia and LOHC had been identified in many studies as optimal hydrogen vectors in terms of techno-economics. Thus, Morocco could, in the future, be one of the leading players of the green ammonia commodity and could deliver the green hydrogen to its clients around the world.

In addition to green ammonia, Morocco's unique geographical situation enables it to deliver the green hydrogen to the EU via pipelines, either by blending it with natural gas in the existing infrastructure or by constructing dedicated ones.

Furthermore, in the mid and long term, other domestic and export market opportunities may arise, mainly in the synthetic fuel segments as well as in the heavy mobility sector, such as logistics, mines, maritime, and aviation. Finally, in the long term, the energy storage applications, industrial and residential heat, as well as urban mobility may become relevant for the country.

**In order to get to the deployment of such a competitive green hydrogen economy in Morocco, the following recommendations for taking action were made:**

- Preparing favorable conditions for exports, mainly to the EU, given its carbon neutrality strategy, such as regulation, permitting, and infrastructure
- Together with international partners and stakeholders, contributing to cost reduction efforts along the whole PtX value and supply chain by encouraging local industrial content via capacity building, training, and technology transfer to Moroccan companies
- Establishing a Moroccan industrial cluster, gathering national and international companies, institutions, and R&D stakeholders to foster the emergence of the first demonstration and commercial projects at scale
- Creating a national and regional R&D hub in order to foster applied research to test, adapt, and scale green hydrogen technologies through R&D and industrial pilot projects and demonstration units
- Developing a domestic market for green hydrogen by encouraging the private sector and investors to produce and use green hydrogen and molecules in multiple industrial sectors (such as steel, agrobusiness, chemicals)
- Fostering international partnership and cooperation in order to leverage financing and elaborate funding schemes capable of triggering the first projects (subsidies, carbon taxes, quotas, premium prices)

In this regard, Morocco had established many cooperation agreements with Germany, the EU, Portugal, and IRENA. Morocco also has a Memorandum of Understanding (MoU) on green hydrogen with the World Bank, Kreditanstalt für Wiederaufbau
(KfW), and the European Bank for Reconstruction and Development (EBRD). Morocco is also a member of Mission Innovation, the MENA Hydrogen Alliance, Hydrogen Europe and Hydrogen Europe Research, the World Energy Council, DENA's PowerFuel Alliance, and the HYPOS research network.

## 7.3 Green Hydrogen in Morocco: First Steps and Ongoing Activities

In 2019, in order to monitor national activities and create synergies among the Moroccan stakeholders, the Ministry of Energy, Mines and Environment created the National Commission of Green Hydrogen (NCGH2) together with **the main following institutions:**

- Ministry of Industry
- Ministry of Finance
- Ministry of Equipment and Transport
- Office Chérifien des Phosphates (OCP Group)
- Office National des Hydrocarbures et des Mines (ONHYM)
- Office National de l'Electricité et de l'Eau Potable (ONEE)
- Moroccan Agency for Solar Energy (Masen)
- IRESEN
- Confédération Générale des Enterprises du Maroc (CGEM)

During 2020, the members of the NCGH2 worked together to elaborate the Moroccan Hydrogen Strategy in order to optimize its deployment with relevant cross-sectoral boundary conditions. Currently, the NCGH2 is conducting follow-up in-depth studies to carry out the action plan defined by this strategy.

In addition to the NCGH2, Morocco witnessed earlier this year the establishment of the Green Hydrogen Cluster "GreenH2 Maroc: Research-Innovation-Industry", founded by nearly 40 Moroccan companies, R&D centers, and universities.

**“GreenH2 Maroc” is operational and consists of the following 6 committees:**

- Energy and Green Molecule Transport
- Renewable Energy Industry
- Chemical Industry
- Green Hydrogen Projects
- R&D and Innovation
- International Partnership

Those two organizations are now working on a complementarity basis and preparing follow-up and detailed studies in order to execute the Moroccan Hydrogen Strategy and its corresponding action plan, taking into consideration some priorities, **such as:**

- Regulation and legal framework
- PtX market triggering and deployment
- Infrastructure and land use
- R&D and Innovation roadmap
- Reinforcement of partnerships and international cooperation

In parallel with these advances on the organizational side, some concrete projects are being developed by several key stakeholders. For instance, an industrial project of 100 MW electrolysis capacity is in a feasibility study phase by Masen. The project should be operational by 2025 and should deliver around 10 000 t/year of green hydrogen. Moreover, many other private and public companies have launched their own (pre)feasibility studies in order to foresee applications for green hydrogen in their specific processes (steel production, agro./food industry, chemical industry, energy storage, sustainable mobility).

On the R&D and innovation side, a dedicated research infrastructure the “Green Hydrogen and Applications (Green H2A) Platform” is under development and should be ready for deployment by early 2022. This facility, a joint-venture between IRESEN and University Mohammed VI Polytechnic (UM6P), aims towards testing, adapting, and upscaling PtX technologies by involving key national and international partners. The focus will also be given to prototyping as well as (pre)industrial piloting and demonstration. The objective is to localize knowledge, know-hows, and intellectual property and make them available to all partners. Furthermore, the platform will be a strong tool for capacity building, training, and preparing a highly qualified human capital for PtX research and industry. Therefore, the Green H2A Platform will help create value and high-skilled jobs in the country for this sector. One of the first projects of the Green H2A Platform will be the ‘Green Ammonia Pilot Plant’, which consists of 4MW electrolysis capacity and a production capacity of around 1300t/year of green ammonia. All these developments are made in a close collaboration with OCP Group, a leader in the phosphate-based fertilizers market, which imports nearly 2 million tons per year of ammonia. This major national stakeholder is strongly interested, along with other partners, in deploying green ammonia production at large-scale, once a business case is achievable.

## 7.4 Conclusion and Perspectives

Like many countries in the MENA region, Morocco is blessed with an exceptional solar and wind potential, which enables it to perform world class competitive prices for green hydrogen and green molecules. The country started relatively early (end of 2017) to consider this opportunity and structured itself to be ready for the deployment of a hydrogen economy in the region.

For this sake, Morocco carried out exploratory and in-depth studies, enabling it to be the first country in MENA and Africa to publish its National Hydrogen Strategy in August 2021 with a corresponding action plan, targeting both the export and the domestic markets. Besides, Morocco has prepared a convenient institutional framework to monitor the developments of green hydrogen advances in the country in a complete synergy among the multiple stakeholders. This was achieved by creating the NCGH2 as well as the Green $H_2$ Maroc industrial cluster.

Another strategic tool under deployment is the Green H2A Platform. It is an R&D infrastructure, which will play a key role in maximizing the value creation of the PtX research and industry by fostering capacity building and enhancing tech transfer.

Moreover, the country is already paving the way for the development of concrete green hydrogen projects at different sizes and for different applications. One such project is the Green Ammonia Pilot Plant, which will be commissioned by 2023 and will consist of around 4MW electrolysis capacity, producing more than 1300 t/year of green ammonia. Another project being developed is an industrial plant of 100MW electrolysis capacity and 10,000 t/year of green hydrogen production rate to be commissioned by 2025.

Finally, Morocco has joined multiple international alliances and has made strategic partnerships with other key countries and stakeholders that will play a major role in the deployment of the green hydrogen economy. Nevertheless, a ‘horizontal’ cooperation scheme among MENA countries is essential as well in order to protect their interests and maximize their positive economic impact, seeing as they will be leading the world in green molecule exports.

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Friedrich-Ebert-Stiftung's Regional Climate and Energy Project in the Middle East and North Africa (MENA) has commissioned, edited, reviewed, and published this study.

**Year 2022**

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The Regional Climate and Energy Project MENA advocates for an energy transition into renewable energy and energy efficiency. It continues to search for just transition solutions in the energy sector that ensure both, the protection of the planet and the people.

As the MENA region is one of the areas most heavily affected by climate change, we contribute to policy advising, research, and advocacy in the areas of climate change policy, energy transition, and urban sustainability, with the support of research institutions, civil society organizations, and other partners in the region and Europe.

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