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The Potential of Green Hydrogen and Power-to-X Utilization in Jordanian Industries: Opportunities and Future Prospects

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Abstract: Green hydrogen and power-to-X technologies hold significant potential in the global energy transition towards net-zero emissions. This is attributed to the premise that these technologies can decarbonize numerous sectors worldwide by providing versatile and sustainable energy carriers and industrial feedstocks to replace fossil-based fuels and chemicals. To this end, the qualitative benefits of green hydrogen and power-to-X technologies have been thoroughly examined for various applications in past years. In contrast, quantifying the potential penetration of such technologies on national and global levels still requires extensive research. Therefore, this paper investigates the prospective integration of green hydrogen and power-to-X technologies within Jordanian industries, considering their quantitative utilization potential for current and future capacities. The findings showed that the Jordanian food processing and heavy industries emerged as major sectors with substantial potential for incorporating green hydrogen and power-to-X products as alternative fuels or chemical feedstocks. In detail, the total potential utilization capacity for these sectors stood at around 57 thousand tons per year. Specifically, fertilizers production, cement industry, steel reforming, and oil refinery possess an annual potential capacity of around 6.8, 11.8, 12.7, and 25.8 thousand tons, respectively. It is also worth mentioning that the current utilization capacity of hydrogen in Jordanian industries was found to be around 8.9 thousand tons per annum, which is completely covered by fossil-based hydrogen to date. These results imply that there will be a promising market for green hydrogen and power-to-X utilization in Jordanian industries, which will play a significant role in integrated energy transition efforts in the future.

Keywords: market analysis; industrial decarbonization; clean energy; green hydrogen; power-to-X; hydrogen applications; Jordan context

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1. Introduction

In the current drive for global decarbonization towards global sustainability, the production and utilization of green hydrogen and Power-to-X (PtX) have become a preferred approach to mitigating and controlling CO_2 emissions in various sectors worldwide [1–4]. Accordingly, global prospects imply that the demand for green hydrogen will significantly rise in the upcoming years [5]. Green hydrogen can be directly utilized in the transportation and industrial sectors as an energy carrier. Further, it can also serve as a chemical feedstock in PtX processes. In other words, green hydrogen produced via water electrolysis powered by renewable energy can be chemically reacted with carbon or nitrogen to produce synthetic fuels or ammonia, which are, in this context, PtX products [6–9].

Moreover, the International Energy Agency (IEA) [10] foresees that the demand for hydrogen is expected to propagate by a factor of six between 2020 and 2050. In detail, global hydrogen demand is expected to grow from 87 Megatons (Mt) in 2020 to 528 Mt in 2050 [10]. This demand can be broken down on a sectoral basis, as illustrated in Figure 1.

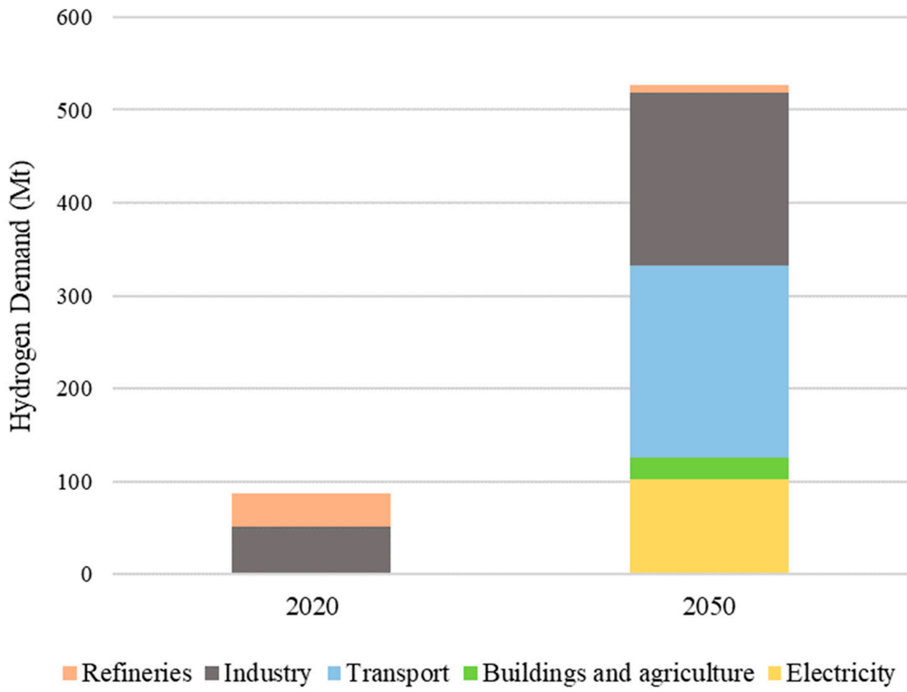

Figure 1. Current and potential global demand for hydrogen on a sectoral basis [10].

As shown in Figure 1 above, the demand for hydrogen is expected to grow significantly before the year 2050 to align with global climate actions and net zero transition in different sectors. For example, the demand for hydrogen in the industrial sector (including oil refinery, cement production, steel manufacturing, and chemical and pharmaceutical industries) is expected to grow from 87 Mt in 2020 to 218 Mt by 2050, accounting for 41.3% of the overall demand for the same year. On the other hand, other sectors are expected to emerge as hydrogen consumers by 2050, including the electricity and transport sectors. In detail, the transport sector can potentially become the second largest hydrogen consumer, with an annual consumption of 207 Mt, especially for long-haul freight, aviation, and shipping. Moreover, electricity generation via fuel cells is expected to consume 102 Mt of hydrogen annually [10]. Therefore, green hydrogen is expected to play a pivotal role in decarbonizing different sectors worldwide, especially in the industrial field. This is due to the fact that hydrogen is already being utilized as a chemical feedstock in significant quantities within numerous industries. Hence, in many cases, decarbonizing the industrial sector will only require shifting from grey hydrogen to green hydrogen without the need for substantial modifications to the existing infrastructures. However, the applicability of this shift is pertained to the future cost of green hydrogen. Currently, green hydrogen costs around \$4–6/kg, which is two to three times more than the cost of grey hydrogen [11]. With the accumulation of global efforts towards net-zero emissions by mid-century, the cost of green hydrogen can drop below \$1.5–2/kg, making it an economically viable alternative to replace grey hydrogen [12]. In contrast, the integration of green hydrogen and PtX technologies in the transport and electricity sectors is not only linked to the cost of green hydrogen but is also contingent on the development of fuel cell technologies, making the decarbonization of these two sectors more challenging and subjected to higher uncertainty levels [13].

Unfortunately, the global economy has been developed depending on fossil fuel consumption in various forms, such as gasoline, natural gas, and other types of fuels. 80% of global energy comes from fossil fuels, posing a crucial threat to the environment and the sustainability of the planet [14]. Replacing the current global economy with another environmental one is a significant challenge due to the immense reliance on fossil fuels and fossil-based chemicals in different sectors worldwide. In contrast, green hydrogen technologies can potentially alleviate much of this environmental burden by providing versatile and clean fuels and chemicals through PtX processes. These processes only require renewable energy systems and carbon dioxide and nitrogen oxides, which could be chemically produced or captured from the current industries to achieve neutralization [15]. The PtX products can be used in a wide range of utilization prospects without the need to modify current infrastructures. For instance, ammonia is currently used in numerous applications such as fertilizers, refrigeration, and water purification [16]. About 85% of the produced ammonia is globally utilized to produce fertilizers [17]. However, it can potentially act as an energy carrier for storing and transporting green hydrogen in the future [18,19].

Numerous studies have investigated the applicability and technical readiness of green hydrogen and PtX technologies worldwide. For instance, Chehade et al. [20] conducted a comprehensive review in which they analyzed 192 existing demonstration PtX projects in 32 countries worldwide to assess the technical readiness level of green hydrogen and PtX technologies. The authors considered the maturity, legality, and technical complexity of all projects, concluding that the advancement in the green hydrogen theme has been satisfactory and rapidly improving in recent years [20]. In contrast, in a study conducted by M.G. Rasul et al. [21] to assess the technical and commercial readiness of green hydrogen technologies, it has been approved that the technical level of green hydrogen systems is adequate, but the commercial readiness level of these systems still requires significant efforts to actualize the green hydrogen economy worldwide [21].

Moreover, many studies were dedicated to examining the possible areas of integration for green hydrogen and PtX technologies. For example, Alexandra M. Oliveira et al. [22] examined the potential role of green hydrogen in the global energy sector. The authors concluded that green hydrogen has the potential to decarbonize 18% of all energy-related sectors worldwide and can aid in transforming global electricity generation towards 100% Renewable Energy (RE) generation by providing the necessary means for renewable energy storage [22]. On the other hand, Barbara Widera [23] reviewed the possible areas of integration for green hydrogen technologies for energy storage, transportation, and other energy-related stationary applications. The author concluded that green hydrogen technologies can play a crucial role in decarbonizing the energy sector worldwide by providing a versatile energy carrier that can be utilized in Power-to-Power (PtP), Power-to-Heat (PtH), and Power-to-Gas (PtG) technologies. In these technologies, green hydrogen is produced via renewable energy through water electrolysis and then utilized for generating electricity via fuel cells, generating heat via hydrogen boilers, or producing synthetic fuels such as methane for different applications [23]. Moreover, Saurav Sanke et al. [24] examined the possible role of hydrogen and PtX technologies in decarbonizing the global transport sector. In their review, the authors concluded that there is a substantial decarbonization potential for the transport sector arising from utilizing PtX products for stationary and mobile applications in the future [24].

In order to invest in green hydrogen and PtX technologies, the potential consequences on global and national markets shall be thoroughly examined and identified. Hence, extensive research efforts have been dedicated to unraveling this potential, considering several aspects in recent years. For instance, Schnuelle et al. [25] conducted a sociotechno-economic of PtX in Germany in terms of possibilities and challenges. The technical and social limitations and economic prospects were assessed in both the centralized and decentralized concepts. The study revealed that despite the high investment cost, it is still reasonable once the environmental considerations and their consequences in the future are considered [25]. Another study by Skov et al. [26] analyzed the limitations and opportunities of PtX in Denmark. The Analytic Hierarchy Process (AHP) was used to assess and compare expert perspectives, concluding that the main challenge is not the technical part but the legislation frameworks. According to the study, concise legalization is the key factor that could influence moving forward toward concrete PtX projects [26].

Regarding developing countries, Ersoy et al. [27] conducted a study targeting the Middle East and North Africa (MENA) in terms of production and export of green hydrogen and PtX products. In the study, the authors considered potential stakeholders and the existing infrastructure in different MENA countries. In addition, the study provides brief insights into the potential utilization in the industrial sector. Altogether, the authors concluded that there is a significant potential for deploying green hydrogen and PtX projects in different countries in the MENA region. This has been attributed to the vast potential of renewable energy and the geographical location of the region, enabling it to become the global hub for green hydrogen export [27].

While existing studies offer valuable insights into the field and discuss the general possibilities and challenges of green hydrogen and PtX technologies, they often lack a specific analysis and market sizing approach, particularly within the context of Jordan. This paper recognizes the gap in the literature and addresses it by introducing an approach that goes beyond a general overview and deeply discusses the specific utilization possibilities, quantities, and scenarios within the Jordanian industrial context. The approach provides a detailed analysis of how these technologies can be practically integrated into the local industries. Moreover, this paper will end up with sizing the current and potential market for green hydrogen and PtX products for local utilization in the Jordanian industrial sector.

The following sections will discuss the possibilities and challenges to the green hydrogen and PtX theme for Jordan's context. This will be followed by an assessment of the potential utilization sectors in Jordan. Afterward, the potential Jordanian market size for green hydrogen and PtX products will be quantified and discussed, considering the most important utilization sectors.

2. Opportunities and Challenges for Green Hydrogen and PtX in Jordan

Being located in the heart of the MENA region, Jordan possesses a high RE potential in different forms, such as solar and wind energies [28–33]. Considering solar energy, Jordan has an average annual global horizontal irradiation of 2083 kWh/m^2 and an average annual direct normal irradiation of 2300 kWh/m^2 [34]. These are among the highest values for solar radiation worldwide, which is justified by the geographical location of the country. Moreover, there are 310 sunny days in Jordan yearly, which indicates that solar energy is available almost throughout the entire year [35]. On the other hand, there is a significant wind energy potential in Jordan, especially in the governorates of Aqaba and Al-Tafilah, with maximum mean wind power densities of 600 W/m^2 and 400 W/m^2, respectively [36].

According to PVGIS [37], the monthly global horizontal irradiation for the Aqaba governorate for the year 2020 is illustrated in Figure 2. As depicted in the figure, the maximum radiation is recorded in August with an average value of 235.16 kWh/m^2/month, while the minimum radiation is recorded in January with a value of 169.59 kWh/m^2/month [37].

This immense potential in RE generation in Jordan has led to massive development in installed RE capacities in recent years. According to the National Electric Power Company [38], the installed RE capacity rose from 123 MW in 2015 to 1575 MW in 2021, with solar energy systems contributing to around 60% of this capacity [38]. Moreover, the Jordanian Ministry of Energy and Mineral Resources stated that the proportion of the installed renewable energy in the country's electrical mix was increased to 29% in 2022. This proportion is planned to increase to 50% by 2030 [39]. Thus, it can be observed that Jordan has a significant chance to build a green hydrogen industry by building the necessary infrastructure.

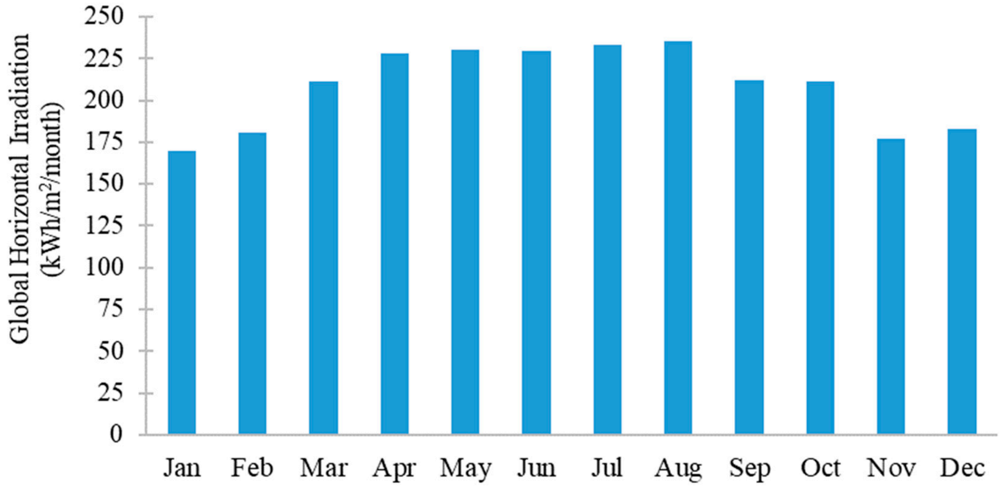

Figure 2. Monthly global irradiation in Aqaba governorate in 2020 [37].

Hydrogen production in Jordan is considered to have significant commercial potential in the near future. The low initial costs of renewable energy systems might attract European companies to invest in green hydrogen at competitive pricing. For instance, the Levelized Cost of Hydrogen (LCOH) has been currently estimated at around \$3.13/kg without accounting for possible governmental incentives or tax exemption [40]. This value is lower than the current global prices for green hydrogen production (\$3.2–\$7.7/kg) and already meets with the optimistic global targets set by the IEA for the year 2060 (\$1.3–\$3.3/kg) [41]. Therefore, this promising technology is seriously considered in every future planning of Jordan's development, such as the economic modernization vision that considers enacting legislation that facilitates the use of green hydrogen and attracts investments in this technology [42]. Jordan has the potential to establish Hydrogen projects and PtX industries. South Jordan, in particular, has a high potential for renewable energy and already has different projects for PV and wind farms. However, water scarcity is a matter in Jordan which necessitates locating Green Hydrogen projects in a coastal location. Aqaba can be considered the best strategic location for hydrogen production and exporting green ammonia or green hydrogen to Europe because of the availability of seawater and potential desalination, the availability of an ammonia port terminal; East Berth of JIPC will be used to import or possibly export liquid ammonia, and the proximity to various unoccupied areas with high RE potential.

One of the critical challenges in the hydrogen production stage in Jordan is water resources limitation. It is crucial to ensure that the availability of water for the local population in Jordan remains unaffected during hydrogen production. Therefore, a water desalination plant can be constructed in Aqaba by the Red Sea to overcome this obstacle. To stay within the scope of green energy, the desalination plant should rely on renewable energy resources throughout the entire process [43]. Jordan has different water resources: river water, dam water, groundwater, treated wastewater, and treated seawater. According to the following, utilized water in Jordan is derived from three main resources: 27% of the water comes from surface water, 59% from groundwater, and 14% from treated wastewater. Further, the safe yield abstraction quantity from non-renewable groundwater for fifty years is about 143 million Cubic Meters (MCM). Regarding the treated wastewater, twenty-seven operating wastewater treatment plants (WWTP) in Jordan are designed to treat 407,930 cubic meters per day [44,45].

Water in Jordan is mainly used for agriculture (51%), homes (45%), and industry (4%). Some water quantities are produced from seawater as there are small desalination plants in operation. A large-scale water plant in Aqaba is planned to be implemented, targeting the production of 130 MCM of water per year. This desalinated water is also planned to be transmitted to Amman through a pipeline (Aqaba Amman Water Desalination and

Canal Project, AAWDCP). With regard to Jordan's water utilization, the annual use is approximately 1093 MCM.

According to the National Water Strategy 2023–2040, future water supplies will largely depend on the desalination of seawater and reclaimed water. The transformation toward utilizing these resources will be increased based on the 2040 strategy. For the industrial sector, for instance, the current and planned water resources and the proportion of the share of each source in MCM are presented in Figure 3. The dependence on seawater will be initiated and is expected to reach 40% of the total share, while groundwater's contribution will decrease to 35% in 2040 [45].

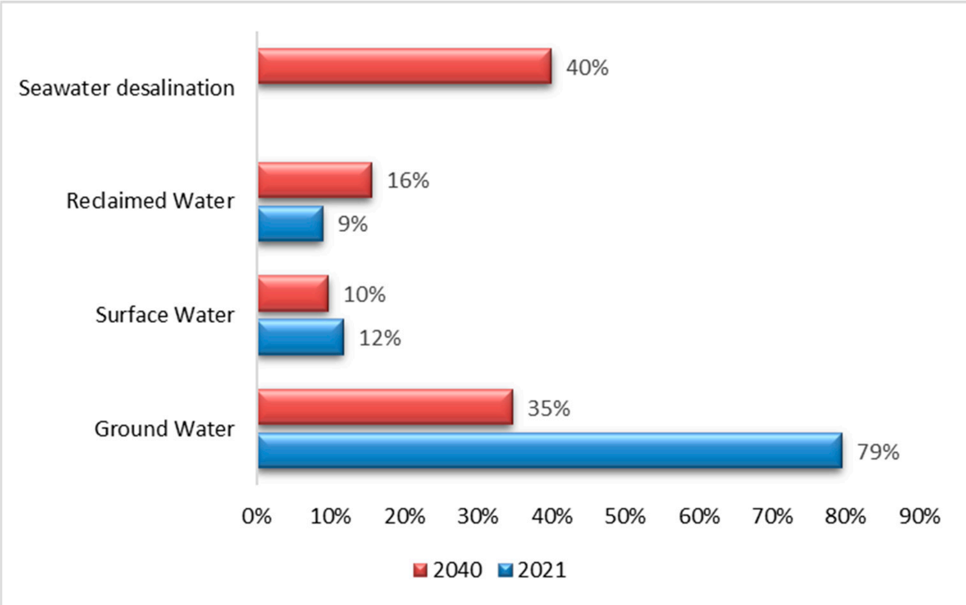

Figure 3. Water Resources in Jordan; current and planned [44].

3. Green Hydrogen and PtX Utilization in the Jordanian Industrial Sector

Hydrogen has great potential to reduce carbon emissions across different industries, including the iron and steel industry, fertilizers production, chemical industry, refining, cement, and aluminum recycling. The potential aspects of green hydrogen and PtX utilization in the industrial sector in Jordan can be categorized into heavy industries, food industries, and pharmaceutical industries. Figure 4 represents the industries that can potentially be candidates for utilizing green hydrogen and PtX in Jordan.

3.1. Heavy Industries

"Heavy industries" refers to a broad spectrum of applications that differ from one source to another. Although, in this context, it will be exclusively regarded as the field of industries including steel, cement, and crude oil refining.

3.1.1. Steel Industry

Hydrogen utilization in the iron and steel sector involves the operation of combustion in blast furnaces for ironmaking. In this process, coke is utilized to generate heat and melt iron. Hydrogen incorporation in this process helps in increasing the temperature of blast furnaces. It facilitates the chemical reaction between the oxygen in the iron ore and the carbon electrodes in the coke to reduce the ore to iron. Accordingly, the heat intensity of the blast furnace will be enhanced due to the retrofitting of the equipment with hydrogen [45].

Examples of well-known and significant players in the steel industry in Jordan are National Steel Industry CO.LTD and Jordan Steel Group [46–48]. The National Steel Company was established in 1979 with an annual manufacturing capacity of 70 thousand tons of steel bars. The production capacity and quality of the company have recently been developed to meet higher standards. This resulted in an annual capacity exceeding 120 thousand tons of top-quality steel bars across various diameters [47].

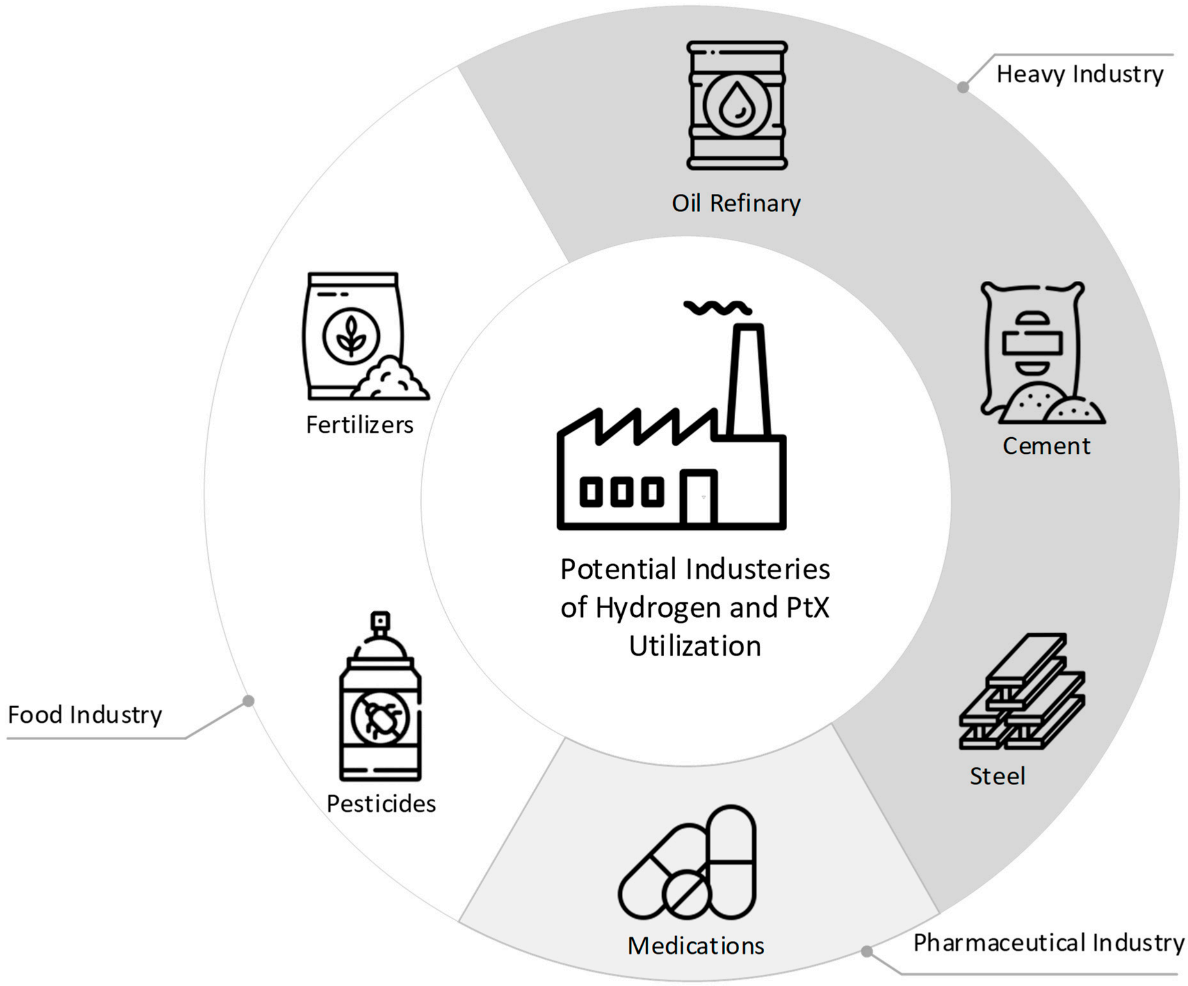

Figure 4. Potential Aspects of Green Hydrogen and PtX Utilization in Jordanian Industrial Sector.

On the other hand, Jordan Steel Group was established in 1993 as a publicly traded company with an initial capital of 35 million JD. The annual production capacity reaches 50 tons of electric furnace, translating to approximately 360 thousand tons of billets, nearly 250 thousand tons of steel rebars, around 4 thousand tons of wire mesh, and roughly 30 thousand tons of cut and bend service [48].

Other iron and steel companies exist across Jordan with different capacities, which ensures the significance of exploring the green hydrogen potential in the iron industry in Jordan. Further, green hydrogen utilization in the iron and steel industry and other industries aligns with the global aim of mitigating carbon dioxide emissions.

3.1.2. Cement

The cement industry is among the most carbon-emitting industries worldwide, accounting for around (7–10)% of the total global emissions [49]. Between 1990 and 2019, global CO_2 emissions from the cement industry rose from 0.86 giga Tons of CO_2 ($GtCO_2$) to 2.46 $GtCO_2$, corresponding to an increase of around 186% in 29 years [50]. According to the International Energy Agency (IEA) [51], the direct specific emissions resulting from the cement industry during the stages of production throughout the period between 2018 and 2022 have been stable at 0.58 tons of CO_2 (tCO_2) per ton of cement [51]. Specifically, 40% of these emissions are caused by heating and electrification processes involved in cement production, while the remaining 60% are a result of raw material preparation and clinker production [52]. Cement clinker is a solid intermediate product used for cement production and is produced through heating Alite, Belite, Ferrite, and Aluminate in a rotary kiln at temperatures of up to 1450 °C [53]. Figure 5 represents the main stages of cement production [54]:

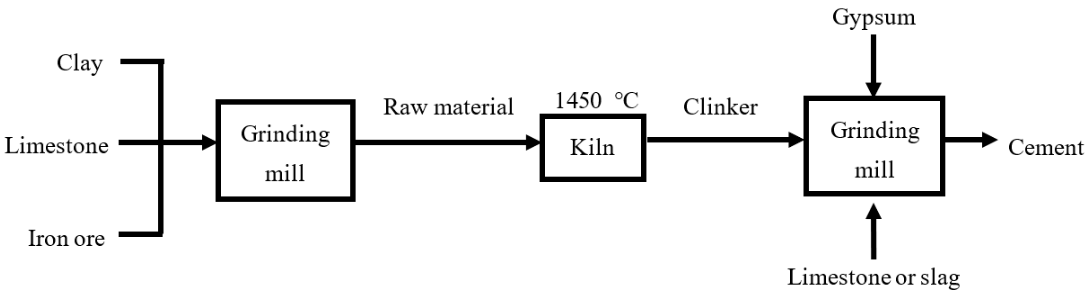

Figure 5. Cement production process.

As represented in Figure 5 above, clay, limestone, and iron ore are mixed and ground in a grinding mill to produce the raw material necessary for clinker production. The raw material then gets heated to around 1450 °C to produce cement clinker in an extensively energy-consuming process. The produced clinker is then mixed with gypsum and limestone or slag to produce cement [54]. The overall process consumes a significant amount of energy, corresponding to large CO_2 emissions. In order to reduce the CO_2 emissions from the cement industry, energy efficiency improvements must be adopted along with the utilization of low-carbon fuels and the substitution of clinker [55].

Green hydrogen offers a promising pathway to decarbonize the cement industry due to its diverse integration opportunities. These include using oxygen and hydrogen produced from water electrolysis for clinker production and capturing CO_2 emissions to be used as a feedstock in PtX operations [56]. For instance, oxy-combustion can replace conventional combustion methods by feeding in a rich stream of oxygen instead of the conventional air mixture necessary for combustion in rotary kilns. This method can improve the quality of cement clinker and reduce the amount of NO_x and CO_2 emissions resulting from the combustion process while producing an exhaust with a dense CO_2 content, which is easier to capture and store [57]. On the other hand, hydrogen can be blended with natural gas-fired kilns to reduce the amount of CO_2 emissions resulting from the combustion process [58]. Further, green hydrogen can be utilized for electricity generation via fuel cells to cover the electricity demand in cement production processes [59]. Altogether, the relationship between the green hydrogen theme and the cement industry is consensual, as green hydrogen can aid in decarbonizing the cement industry, while the latter can provide the necessary carbon for the PtX value chain.

In the case of Jordan, five major companies produce cement in the country. These companies are Lafarge Jordan Cement, Qatrana Cement, Manaseer Cement, Northern-Cement Co., and Cementra Jordan [60]. All operate in the same manner and use similar facilities and equipment with varying production capacities. The latest announced maximum annual capacities for each company is 4 million Ton per year (Mt/year) from Lafarge Cement, 2.4 Mt/year from Cementra, 1.8 Mt/year from Manaseer Cement, 2 Mt/year from Qatrana Cement, and 1 Mt/year from Northern-Cement [61–65]. Altogether, the Jordanian cement industry has a maximum total production capacity of around 11.2 Mt/year, much larger than the local demand of around (3.1–4.1) Mt/year [66]. To date, the integration of Hydrogen technologies is not mentioned in any strategies or announcements from the previously mentioned companies.

3.1.3. Crude Oil Refining

Crude oil refining is the third-largest stationary source of global emissions, accounting for 40% of petroleum and gas lifecycle emissions and 6% of the total emissions resulting from global industries [67]. As for 2020, the global demand for hydrogen stood at around 90 Mega Ton (Mt), from which 40 Mt has been dedicated to crude oil refining, making it the largest consumer of hydrogen worldwide. This demand has been covered by grey hydrogen produced from fossil fuels, which corresponds to carbon emissions of 200 $MtCO_2$ [68]. Replacing grey hydrogen with green hydrogen in oil refining has the potential to reduce the emissions resulting from this sector by 22% [69]. Hence, adequate consideration must be given to promoting the utilization of green hydrogen in crude oil refining.

Crude oil is the 4th most imported product in Jordan. For instance, Jordan imported 12.99 million barrels of crude oil in 2021, with a total cost of $956 million from Saudi Arabia (92.8%) and Iraq (7.2%) [70]. Jordan only has one oil refinery, which belongs to the Jordan Petroleum Refinery Company (JPRC). The JPRC provides Jordan with all petroleum fuels, including gasoline, diesel, aviation fuel, and fuel oil. Also, the company produces other products such as Asphalt, lube oil, Liquid Petroleum Gas (LPG), white spirit, and sulfur [71]. The JPRC currently refines 60,000 barrels of crude oil per day and is working on its fourth expansion to refine 120,000 barrels of crude oil daily [72].

Generally, hydrogen is used in two main processes during oil refinery: hydrotreating and hydrocracking [73]. Hydrotreating consists of processes that aim to remove sulfur, nitrogen, metals, and other impurities from crude oil before the hydrocracking process [74]. This is carried out by feeding crude oil along with large volumes of hydrogen into a catalytic reactor in which several chemical reactions take place in succession. These include hydrodesulfurization, hydrodeoxygenation, and hydrodenitrogenation, which refer to the reactions in which hydrogen is used in the presence of a catalyst to remove the content of sulfur, oxygen, and nitrogen from crude oil, respectively [75]. On the other hand, hydrocracking is a process in which heavy petroleum products are converted into lighter, useful fuels in the presence of hydrogen and a selective catalyst. This process is carried out at low temperatures, resulting in minimal energy consumption.

Further, the catalyst activity in hydrocracking is superior to the one achieved in other methods for petroleum cracking, such as thermal cracking. Also, petroleum products from hydrocracking possess an unmatched quality as they have a high Hydrogen-to-carbon ratio and a low content of impurities [76]. The hydrocracking process is illustrated in the following figure [77]:

As shown in Figure 6, a typical hydrocracker contains a reactor, a separator, and a fractionator. Firstly, preheated crude oil is combined with compressed hydrogen in the catalytic reactor to break long-chain hydrocarbons in an endothermic reaction to produce short-chain hydrocarbons, which in turn go through an exothermic hydrogenation reaction in which they combine with hydrogen to produce saturated short-chain hydrocarbons. The reactor typically operates at a temperature between 300 °C and 450 °C and a pressure of between 80 bar and 200 bar. The products from the catalytic reactor are then sent to a high-pressure separator in which unreacted gaseous hydrogen is sent back to the catalytic reactor, and the liquid-saturated short-chain hydrocarbons proceed to the fractionator. In the fractionator, useful fuels such as diesel, gasoline, naphtha, kerosene, and other fuels are extracted from saturated short-chain hydrocarbons, and the excess crude oil is recycled to the catalytic reactor to undergo the hydrocracking process [77].

According to the research and development team at the JPRC [78], the JPRC's demand for pure hydrogen is around 700 kg/h (5.88 million kg/year), which is consumed for hydrotreating and hydrocracking processes. This demand is covered through two streams for hydrogen production, which are the hydrogen reforming plant stream and the fixed-bed platforming unit stream. The hydrogen reforming plant produces around 500 kg/h of grey hydrogen through naphtha reforming, while the fixed-bed platforming unit produces around 200 kg/h of hydrogen as a byproduct resulting from gasoline enhancement processes. The purity of hydrogen produced from the reforming plant sets around 99.99%, which is significantly higher than the purity of the hydrogen produced from the fixed-bed platforming unit (=65–79%). Furthermore, the JPRC continuously improves its environmental performance to align with global targets and strategies. For instance, the company reduced its GHG emissions from 577 Kilo Ton of Carbon Dioxide (ktCO_2) in 2021 by 3% to 554 ktCO_2 in 2022 and increased its reliance on renewable energy resources by 50% for the same period. Thus, the JPRC might consider shifting its operation to rely on green hydrogen rather than grey hydrogen, especially if the cost of green hydrogen becomes competitive with that of grey hydrogen in the future [78,79].

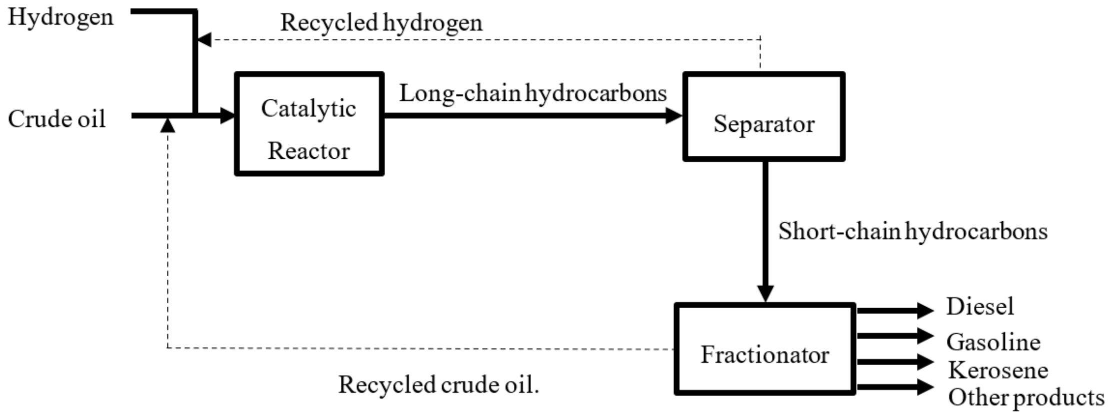

Figure 6. Hydrocracking of crude oil [77].

3.2. Food Industries

There are many indirect but significant relations between green hydrogen technologies and food industries. These relations are most clearly manifested in the potential of fertilizer production through green ammonia, which can be produced from green hydrogen. Hence, in this context, the production of green ammonia and fertilizers will be considered as the main area of integration for green hydrogen and PtX within the Jordanian food industry.

3.2.1. Fertilizers

Green ammonia is one of the most promising green hydrogen derivatives that could be produced for local use and export purposes in Jordan. Generally, ammonia is commonly used for producing fertilizer, plastics, and different processes such as oil refining and steel production [80]. There are various applications in Jordan, contributing significantly to the country's agricultural sector.

As previously discussed, there is a significant potential for renewable energy and, thereby, green hydrogen production for both local use and export purposes. Various projects and partnerships have been initiated to start studying and applying green hydrogen technology in Jordan. Jordan's Fidelity Group and Poland's Hynfra have established Jordan Green Ammonia L.L.C., which aims to construct a green ammonia plant within Jordan's Aqaba Special Economic Zone. The project encompasses the development of a renewable ammonia synthesis plant, a 530-megawatt PV farm, a seawater desalination station, and an energy storage facility [81].

The estimated ammonia production ranges between 100,000 and 200,000 annually. Part of the ammonia produced will be sold in local markets, and the majority will be exported to European Union (EU) countries. Besides Ammonia production, this project will generate various other green energy outputs such as green heat, hydrogen, oxygen, and industrial steam. The entire plant is expected to become operational within a five-year timeframe [80].

Jordan has an existing market for ammonia trading, import, and export. A report from "TrendEconomy open data portal" provides annual international trade statistics for ammonia for the years 2011 to 2022 [82]. The data covers Jordan's imports and exports of ammonia, highlighting key trends and figures. In 2022, Jordan's exports of ammonia amounted to $45 thousand, indicating a significant 64% decrease in value compared to the previous year, 2021. The primary export destinations were Sudan (44%), Saudi Arabia (28%), and Lebanon (26%) [81]. On the other hand, Jordan's imports of ammonia totaled $153 million in 2022, reflecting a notable 22% increase from the previous year, 2021. The major sources are Saudi Arabia (40%), Algeria (18.8%), and Egypt (13.8%).

The primary use of ammonia in Jordan is in the production of fertilizers. The fertilizer industry is considered one of the main aspects that needs hydrogen derivatives in its manufacturing. The fertilizers contain nitrates, such as Ammonium Nitrate (AN) and calcium Ammonium Nitrate (CAN). Other nitrogen fertilizers include ammonium sulfate, ammonium sulfate nitrate, anhydrous ammonia, etc. Ammonia is a crucial component in the manufacturing of nitrogen-based fertilizers, such as Di-Ammonium Phosphate (DAP). The fertilizer industry is considered to be one of the main aspects that need hydrogen derivatives in its manufacturing [82]. The process of utilizing hydrogen in the fertilizers industry involves the application of RF plasma technology. In this method, hydrogen is introduced as a key ingredient and subjected to RF plasma, which is a state of ionized gas induced by radio frequency waves. Within this controlled environment, hydrogen reacts with nitrogen to produce ammonia (NH3), a crucial component in fertilizers. On the other hand, nitrogen oxides are formed and further processed to generate nitric acid (HNO_3), another essential compound for fertilizers. The synthesis of ammonia and nitric acid ends in the creation of ammonium nitrate (NH_4NO_3), a widely used nitrogen fertilizer in agriculture [82], see Figure 7.

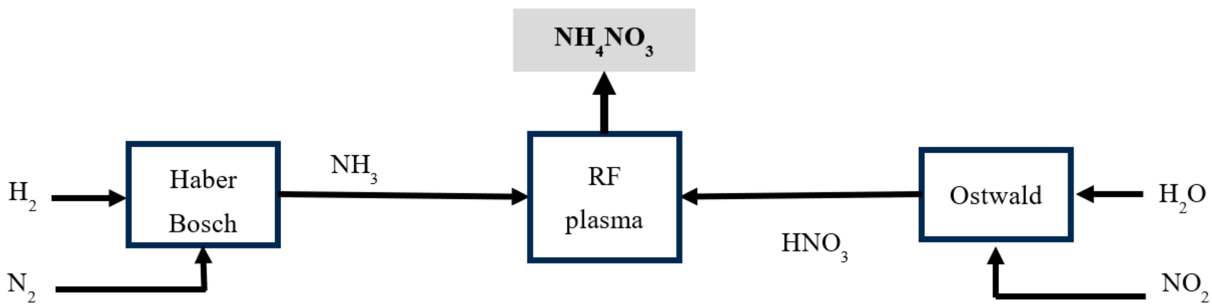

Figure 7. The process of utilizing hydrogen in the fertilizers industry.

In Jordan, there are potential domestic users of ammonia in fertilizer production, such as the Jordan Phosphate and Mining Company (JPMC) and the Arab Potash Company (APC). The availability and diversity of the local users of Green Hydrogen and PtX will pave the way towards accelerating the investments in this technology for both the local and export sectors, as the current ammonia used in Jordan is imported from various Arab and foreign nations.

3.2.2. Pesticides

The agricultural industry in Jordan utilizes ammonia to produce pesticides. These pesticides also play a critical role in protecting agricultural investments and ensuring stable food production. Hydrogen has potential applications in the field of agriculture and pest management, especially within the framework of sustainable and environmentally friendly methods.

Hydrogen peroxide is a chemical compound that compresses hydrogen and oxygen. It is a common ingredient in disinfectant items and is also approved for controlling microbial pests on crops and specific crops during the post-harvest phase. Hydrogen peroxide controls the growth of bacteria and fungi responsible for significant plant diseases. Further, it can rapidly decompose into oxygen and water in the surrounding environment. Using Hydrogen peroxide by following the directions and instructions will enable users to utilize the product without any effects on humans or the environment [83].

3.3. Medical and Pharmaceutical Industries

Green hydrogen has significant attention in medical applications based on several studies and experiments conducted on humans and animals. These experiments proved the effective role of hydrogen in the treatment of diverse diseases. The therapeutic impact of hydrogen has stemmed from its effective antioxidant action in eliminating Reactive Oxygen Species (ROS). Examples of ROS diseases that have been positively affected by hydrogen utilization are diabetes, renal complications associated with dialysis, acute brain infarction, skin inflammations, side effects of radiotherapy, and skin aging [84].

Studies show that hydrogen gas has several advantages over conventional antioxidants. Firstly, hydrogen can traverse through the cell membrane, which facilitates its distribution to all organs and tissues. Secondly, hydrogen can eliminate the most harmful and toxic Hydroxyl radicals (.OH) of ROS. Lastly, all the experiments proved that the doses of (0.4 and 1.6 ppm) have no negative or toxic effects [85].

Hydrogen can be utilized in manufacturing various precursors in the pharmaceutical sector, including hydrogen peroxide, table sugar, and hydrochloric acid. Hydrogen peroxide is an antiseptic used typically to protect against infections in burns and small cuts. It can also be served as a mouth rinse. Within the biomedical sector, hydrogen peroxide has demonstrated its effective functionality as an oxidizing agent compared to other harmful oxidants such as chromates and hypochlorite [86].

The pharmaceutical sector in Jordan encompasses a group of companies engaged in manufacturing, distribution, research, and development. These companies include Hikma Pharmaceutical, 3R Pharmaceuticals, ACDIMA BioCenter, and Dar Al Dawa. These companies play a critical role in providing essential medications and healthcare to the population.

4. Analysis and Discussion

This study aims to explore the prospective applications of Green Hydrogen and PtX technologies within Jordan's context. The study starts by collecting the required data by surveying the potential sectors and the aspects of hydrogen usage in Jordan. Moreover, data is collected from published reports, literature, interviews, and relevant official websites.

The direct and indirect uses of hydrogen or its derivatives are considered the proportion of usage in each industry, and the corresponding hydrogen demand is estimated in the sectors of high potential. As the data on such a topic is insufficient in many sectors in Jordan, the study approach suggests some assumptions and scenarios to accommodate the available data with the paper's scope to evaluate the future potential in Jordan. The methodology of this study is represented in Figure 8:

4.1. Green Ammonia for Fertilizer Production

The total arable land in Jordan is 9 million dunums, but the total current exploited land in Jordan is only 4 million dunums. In order to estimate the needed capacity of fertilizers in Jordan for both scenarios (all arable land and current exploited land), It is necessary to determine the total area in square meters and then calculate the amount of fertilizer required for each scenario, see Table 1:

These calculations are based on the recommended rate of 20 g per square meter. However, the actual fertilizer amount may vary based on specific crop types, soil conditions, and other factors. In order to estimate the ammonia content in the fertilizers, such as Ammonium nitrate, it is necessary to estimate the weights chemically. Generally, the ammonia (NH_3) content in ammonium nitrate is 21.2%. This is estimated based on the chemical composition, as ammonium nitrate (NH_4NO_3), the weights of nitrogen, hydrogen, and oxygen are 14, 1.008, and 16, respectively. Thus, the total weight of the ammonium nitrate compound is 80, while the ammonia NH_3 weight is 17 g/mole, which occupies 21.2% of the ammonium nitrate.

Table 1. Scenarios of current and potential use of fertilizers in Jordan.

Parameter \ Scenario	Current Capacity	Expected Capacity
Area in m^2	4000 (km^2)	9000 (km^2)
Amount of fertilizer needed	80,000 (tons/year)	180,000 (tons/year)
Amount of ammonia needed	16,993 (tons/year)	38,160 (tons/year)
Hydrogen capacity needed	3024.75 (tons/year)	6792.48 (tons/year)
Energy needed to produce Hydrogen	119.17 (GWh/year)	267.6 (GWh/year)

Facts and Assumptions:

- 1 dunam equals 0.001 km^2 equivalent to 1000 m^2.
- Recommended rate of fertilizers is 20 g per m^2 [87].
- Approximately 178 kg of hydrogen are needed to produce one ton of ammonia [88]
- The ammonia (NH_3) content in ammonium nitrate is 21.2%.
- 39.4 kWh is needed to produce 1 kg of H_2 [89].

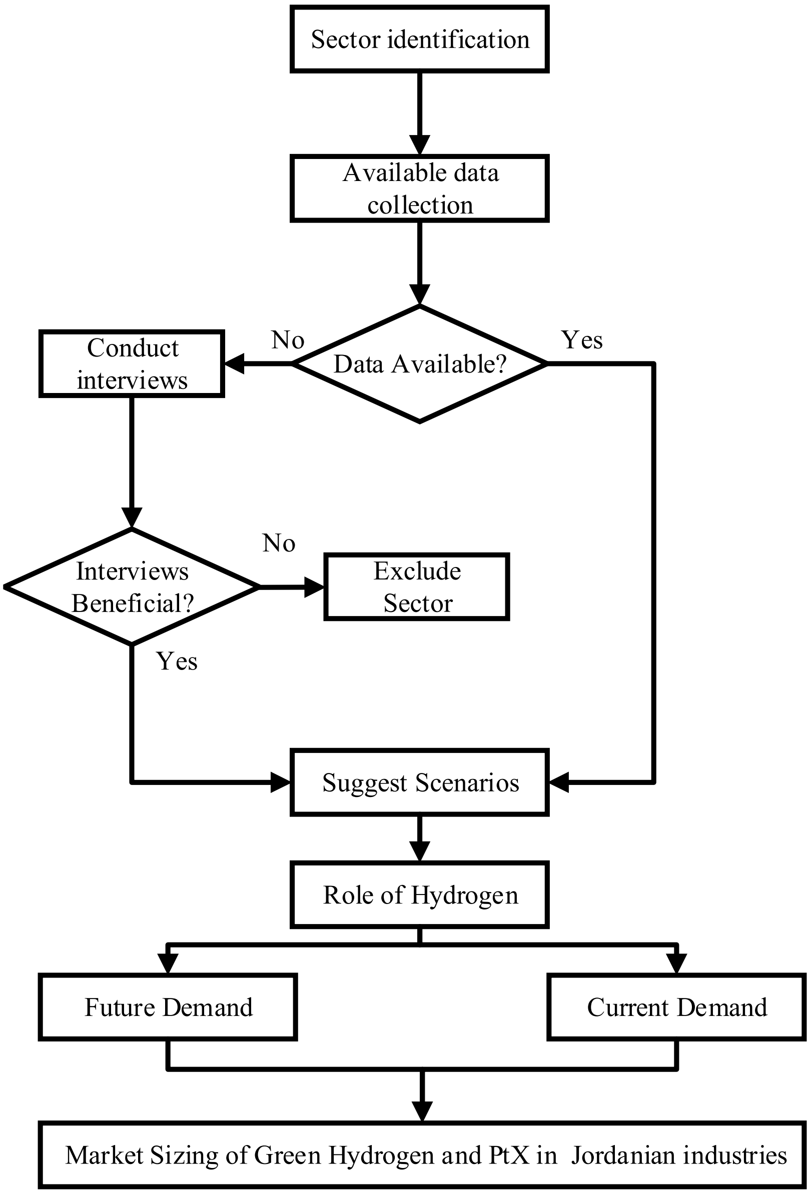

Figure 8. Analysis Methodology.

4.2. Steel Industry

According to the Jordan Steel Group, the amount of manufactured steel in Jordan is about 250 thousand metric tons. Decarbonizing this industry requires the use of green resources such as Green Hydrogen. Hydrogen in the steel industry can be used as an alternative injection to pulverized coal injection (PCI) or as a reductant substitute for natural gas. Typically, to produce 1 ton of steel using Hydrogen Direct Reduction (H-DR), 51 kg of hydrogen is needed [90]. Thus, for the Jordanian context, the decarbonization requirements based on using Green Hydrogen are illustrated in Table 2:

Table 2. Hydrogen Requirements for Steel Industry Decarbonizing in Jordan.

Parameter	Values
Steel Quantity	250,000 (tons/year)
Hydrogen capacity needed	12,750 (ton/year)
Energy needed to produce Hydrogen	502.235 (GWh/year)
Facts and assumptions:	
• 51 kg H_2 per ton of steel in (H-DR).	

4.3. Cement Industry

As stated previously, no clear strategies or intentions are currently relevant to integrating green hydrogen technologies into the cement industry in Jordan. However, this industry has the potential to play a crucial role in decarbonizing the Jordanian industrial sector through the green hydrogen and PtX theme. For instance, in kilns, green hydrogen can be blended with natural gas to alleviate some of the adverse environmental impacts of combusting natural gas. Also, green hydrogen can be utilized in fuel cell systems to generate the electricity required for operating cement factories. On the other hand, oxygen produced from water electrolysis can be used in oxy-combustion in kilns to reduce harmful emissions. Last but not least, the unavoidable CO_2 emissions from the cement industry can be captured and utilized to produce hydrocarbon fuels in PtX operations. Altogether, the cement industry is significantly interconnected with the potential of the green hydrogen theme worldwide.

Considering the potential of the green hydrogen theme in the Jordanian cement industry, the annual cement capacity is around 11.2 Mt/year and is not expected to grow in the upcoming years as it already exceeds the current local demand (3.1–4.1) Mt/year. Assuming that Jordanian cement companies will blend green hydrogen with natural gas with a ratio of 1:9, Table 3 applies:

Table 3. Current and Expected Hydrogen Demand in Cement Industry in Jordan.

Scenario / Parameter	Current Capacity	Expected Capacity
Current quantity of cement	11,200,000 (ton/year)	11,200,000 (ton/year)
Energy needed for heating	25,760 (GWh/year)	25,760 (GWh/year)
Energy needed from fuel	29,881.6 (GWh/year)	29,881.6 (GWh/year)
Volume of consumed natural gas	3080.6 (million m^3/year)	2772.5 (million m^3/year)
Volume of consumed Hydrogen	0 (million m^3/year)	308.05 (million m^3/year)
Hydrogen demand	0 (ton/year)	25,799.4 (ton/year)
Facts and assumptions:		
• 2.3 MWh of thermal heat is required to produce 1 ton of cement [91].		
• Natural gas has an energy density of 9.7 kWh/m^3 [92].		
• Combustion efficiency for natural gas is 84%.		
• Density of Hydrogen is 0.08375 kg/m^3 [93].		

Considering that each ton of cement produces 580 $kgCO_2$, the Jordanian cement industry would be responsible for total emissions of around 6.5 million tons of CO_2 emissions. This significant number of harmful emissions can be converted into national wealth if utilized and captured for PtX operations. Specific quantities of PtX products from these emissions rely on the type of fuels and/or chemicals that ought to be produced. On the other hand, considering that 1 million British Thermal Units (MBBTU) (=293.07 kWh) worth of natural gas produce around 53.07 $kgCO_2$ (=0.18 $kgCO_2$/1 kWh) [91], the total emissions directly related to natural gas combustion for cement production would yield a value of 5.4 million ton of CO_2. Blending green hydrogen with natural gas in kilns for cement production can reduce carbon emissions by 10% since green hydrogen does not produce any emissions when combusted, resulting in overall emissions of around 4.87 million tons of CO_2. In such a case, there will be a reduction in the required cost for installing carbon capturing and storage systems while preserving a significant amount of emissions to be captured and utilized for PtX applications.

4.4. Crude Oil Refining Industry

As mentioned previously, the JPRC is the only oil refining company in Jordan, which means that it represents the entire industry in the country. To date, the JPRC refines 60,000 barrels of crude oil per day (=21 million barrels/year) and aims to expand its capacity to refine 120,000 barrels of crude oil daily (=42 million barrels/year). Throughout all processes, the company consumes 700 kg of hydrogen per hour, corresponding to 16.8 tons of hydrogen per day and 5880 tons per year. Assuming that doubling the quantity of refined crude oil would result in doubling the demand for hydrogen, the expected hydrogen demand would increase to 11,760 tons of hydrogen per year. Table 4 summarizes the current and expected demand for hydrogen in the Jordanian oil refining industry:

Table 4. Scenarios of green hydrogen utilization in an oil refinery in Jordan.

Parameter \ Scenario	Current Capacity	Expected Capacity
Current quantity of refined crude oil	21,000,000 (barrel/year)	42,000,000 (barrel/year)
Hydrogen demand	5880 (ton/year)	11,760 (ton/year)
Energy needed to produce Green Hydrogen	231.67 (GWh/year)	463.34 (GWh/year)

Moreover, the current emissions resulting from the crude oil refinery sector in Jordan stand at 571 $ktCO_2$ for a refinery capacity of 60,000 barrels of crude oil per day. These values indicate that each barrel of oil at the JPRC refinery emits around 0.027 $kgCO_2$. Assuming that the emissions would double when doubling the quantity of refined oil, their quantity will reach 1142 $ktCO_2$. Also, assuming that replacing grey hydrogen with green hydrogen will contribute to a reduction of 22%, the total emissions from crude oil refining in Jordan would drop to 891 $ktCO_2$. In other words, refining a barrel of crude oil would emit 0.021 $kgCO_2$ in the case of green hydrogen adoption and without considering emissions reduction resulting from other environmental precautions.

4.5. Potential Market Size

As this study was dedicated to investigating the potential use of green hydrogen and PtX in different industrial sectors, the market potential size is identified in this section. The Sankey chart in Figure 9 summarizes the potential capacities of the Jordanian Market (in tons per year). This figure represents the market size depending on the values resulting from the analysis that has been previously discussed in Section 4. The total annual hydrogen potential capacity that Jordan needs in the energy transition towards green hydrogen and PtX is 57,672 tons. A substantial portion of this demand is allocated to heavy industries (50,309 tons) and the food sector (6793 tons). The total capacity of green hydrogen that is currently in use is 8904.7 tons. Most of this capacity is used for oil refineries in the form of pure grey hydrogen. Although, as previously discussed, the current use of hydrogen or PtX products in fertilizers is in the form of ammonia. In order to align with the energy transition objectives in the industrial sector, there is a need to increase the potential capacity to 48,766.7 tons and adequately address the energy market requirements in Jordan. However, the adoption of hydrogen in such a market faces challenges related to both technology and economics. To establish a sustainable market, it is crucial to overcome these obstacles. One major difficulty is the need for a substantial reduction in the cost of green hydrogen. Lowering the production and transportation costs, as well as the utilization technology costs along with governmental incentives and tax exemption, will make green hydrogen more competitive and viable for various industries, dropping its cost from the current \$3.13/kg to below \$1.5/kg to meet global targets and attract industrial stakeholders. In addition to cost reduction, another significant factor that can accelerate the transition to green solutions, particularly the use of green hydrogen and its derivatives, is the implementation of carbon emissions taxes. By imposing taxes on carbon emissions, policymakers can create economic incentives for industries to shift towards cleaner technologies. This approach encourages the adoption of green alternatives and aligns with global efforts to mitigate climate change.

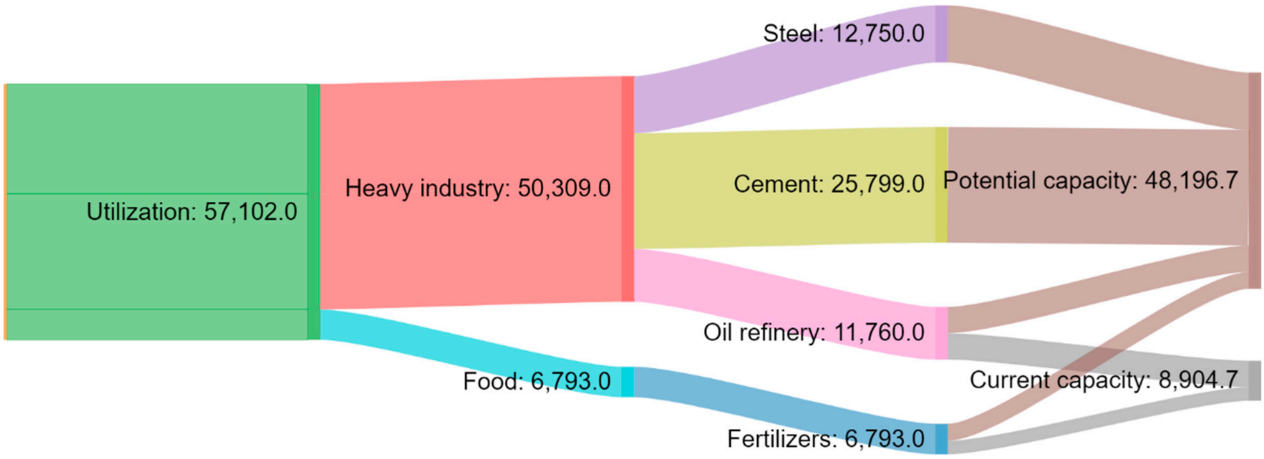

Figure 9. Hydrogen utilization in Jordan: total expected capacity, current and potential use (in tons).

Advancements in hydrogen supply chain technology play a key role in achieving cost reductions. As technological innovations progress, the costs associated with green hydrogen production are likely to decrease, making it more economically feasible for industries to adopt these sustainable solutions. At the same time, implementing carbon taxes provides a regulatory framework that complements technological advancements, pushing industries to consider the environmental impact of their operations. Finally, the convergence of reduced production costs and the implementation of carbon taxes will reach a tipping point. At this stage, green technologies will become increasingly competitive compared to traditional fossil fuel dependencies.

5. Recommendations and Directions for Future Research

In light of the globally emerging green hydrogen and PtX theme, Jordan must invest in unraveling the full potential of such technologies from a local point of view. This must be carried out in close cooperation between the scientific community and policymakers in Jordan to obtain realistic and applicable sustainable solutions. Future research shall explore alternative green hydrogen and PtX possibilities beyond the scope of this study, such as electricity generation and transportation sectors. Moreover, investigating the feasibility of using hydrogen in domestic cooking as a substitute for Petroleum gas and exploring the conversion of hydrogen into other fuels, such as methane and methanol, could lead to a comprehensive understanding of the Hydrogen-based sustainable energy market.

Furthermore, precise techno-economic analyses will hugely aid in the planning and the anticipated actualization of green hydrogen and PtX in Jordan. To this end, this study could be considered as a groundwork for understanding the potential market of green hydrogen and PtX technologies in Jordanian industries.

On the other hand, a key recommendation to Jordanian policymakers and relevant stakeholders is to prioritize investing in the food industry and fertilizer manufacturing utilizing the existing ammonia and fertilizers infrastructure in Jordan. Besides, oil refinery contributes to a significant proportion of the current use of hydrogen in Jordan. Hence, it can crucially participate in the Jordanian energy transition by replacing grey hydrogen with green hydrogen, especially with the global transition toward a green planet and the potential taxes that could be employed for greenhouse gas emissions. Furthermore, green hydrogen holds significant potential in decarbonizing the cement industry in Jordan by providing a versatile and environmental fuel that can be blended with natural gas for heating purposes. Similarly, the same applies to the Jordanian steel-making industry, especially when considering the anticipated environmental regulations on such heavy industries in the future. Altogether, the success of the Jordanian green hydrogen economy is hugely influenced by the actions of policymakers, as active regulations must be established to promote the adoption of the green hydrogen and PtX theme through economic incentives and tax exemption.

6. Conclusions

This paper has examined the promising prospects of integrating green hydrogen and PtX technologies in Jordanian industries, with a specific focus on heavy industries and food processing. Despite the limitations, including limited data availability for various industries, the findings underline the significant potential for integrating green hydrogen as an alternative feedstock or component in key sectors such as green steel, cement, oil refining, and food processing. The estimated current utilization of hydrogen in Jordanian industries is more than 8900 tons annually. Specifically, oil refineries and fertilizer production currently rely on green hydrogen and/or PtX products, which highlights that there is an existing foundation for further integration and utilization. Furthermore, the paper proposes an optimistic outlook for the future, with the potential to increase this capacity to over 57,000 tons to incorporate additional Jordanian industries such as cement production and steel industries. This expansion could play a critical role in advancing the country's energy transition efforts, especially from an environmental point of view to cope with global targets along the path towards a sustainable, clean world.

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