This sector analysis was commissioned by the German Energy Solutions Initiative of the German Federal Ministry for Economic Affairs and Climate Action (BMWK).

Sector Analysis – Jordan

Green hydrogen for the commercial and industrial (C&I) sector

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On behalf of
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Inhalt

Abbreviations/Acronyms

AAWDCP	Aqaba-Amman Water Desalination and Conveyance Project
AC	Alternating current
AEL	Alkaline electrolysis
AEM	Anion exchange membrane
AHK	German Chambers of Commerce Abroad
ASU	Air Separation Unit
bar	Metric unit of pressure
barg	Absolute pressure and gauge pressure
BMWK	German Federal Ministry of Economics and Climate Action
bpd	Barrels per day
CAPEX	Capital Expenditures
CH_3OH	Methanol
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DAP	Diammonium phosphane
DC	Direct current
EFTA	European Free Trade Association (Iceland, Liechtenstein, Norway, Switzerland
EIB	European Investment Bank
EMRC	Energy and Minerals Regulatory Commission
EPC	Engineering Procurement & Construction
ESMAP	Energy Sector Management Assistance Program
EU	European Union
EU ETS	European Union Emissions Trading System
FFI	Fortescue Future Industries Pty Ltd
GHG	Greenhouse gases
GIS	Geographic information system
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
GW	Gigawat
GWh	Gigawatt-hour
H_2	Hydrogen
H2-PDP	Project Development Programme for Green Hydrogen Projects
H2Uppp	International Hydrogen Ramp-up Programme
HLCCP	High-Level Commission on Carbon Prices
JIC	Jordan Investment Commission
JREEEF	Jordan Renewable Energy and Energy Efficiency Fund
KFW	Kreditanstalt für Wiederaufbau
kWh	Kilowatt hour
LCoA	Levelized Cost of Ammonia
LCoH	Levelised Cost of Hydrogen
LNG	Liquefied Natural Gas
LOHC	Liquid organic hydogen carriers
MEMR	Jordanian Ministry of Energy and Mineral Resources
MoU	Memorandum of understanding
MTHP	Maximum Technical H2 Potential
MW	Mega Watt
N_2	Nitrogen
NEPCO	National Electric Power Company
NH_3	Ammonia
OPEX	Operational expenditures
PDP	Project Development Programme
PEM	Proton exchange membrane
PPP	Public-Private Partnership
PtX	Power-to-X
PV	Photovoltaics
RE	Renewable energy, Renewable energy
SME	Small and medium-sized enterprises
SMEs	Small and medium-sized enterprises
SOEC	Solid oxide electrolysis
TIC	Total installed cost
ton	Imperial unit of mass equivalent to 1,016.047 kg or 2,240 lbs
tpa	Tons per annum
tpd	Tons per day
VRE	Variable renewable energy

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Currency Units

EUR Euro
JOD Jordanian Dinar

Conversion 29/06/23: EUR 1 = JOD 0.7747
Note: 1,000 fils = JOD 1

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The German Energy Solutions Initiative

Energy solutions – made in Germany

Launched in 2002 by the German Federal Ministry for Economic Affairs and Climate Action (BMWK), the German Energy Solutions Initiative is primarily aimed at small and medium-sized enterprises (SMEs) and supports suppliers of climate-friendly energy solutions in finding new markets abroad. The initiative is active in around 140 countries and aims to disseminate German and European energy technologies more extensively across the globe.

The initiative includes the Project Development Programme (PDP) which is carried out by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH and promotes climate-friendly energy solutions in selected emerging and developing countries in sub-Saharan Africa, South and Southeast Asia and the Middle East. Since 2007, the PDP has been supporting the energy transition in its cooperation countries by developing concrete renewable energy and energy efficiency projects. The focus was recently expanded to include green hydrogen projects through the Project Development Programme for Green Hydrogen Projects (H2-PDP), as the German Energy Solutions Initiative is increasingly promoting green hydrogen as a crucial energy carrier for achieving a climate-neutral economy.

Project Development Programme for Green Hydrogen Projects (H2-PDP)

Green hydrogen (H2) is needed to reduce the industry carbon footprint. At present, however, countries such as Ghana, Kenya, Jordan and Vietnam primarily use 'grey hydrogen' derived from fossil fuels. The sustainability of a product and its carbon footprint will play a greater role in determining its competitiveness in future, so it is worthwhile for companies to switch from grey to green hydrogen at an early stage. This solution is hardly cost-effective at the moment, but it is expected to become more competitive with the ramping up of this new market. Moreover, German and European technology suppliers and project developers are not currently particularly active in the selected countries. The market is still being established.

The objective of the project is to enable Ghana, Kenya, Jordan and Vietnam to progressively produce green hydrogen at competitive prices. In order to achieve this, the project identifies local companies that are able to switch from producing or consuming grey hydrogen to producing green hydrogen within a short period. It advises them on plant design, financial models and how they can cover the funding gap when compared with grey hydrogen. With a view to accelerating the transition to green hydrogen, the project facilitates access to funding instruments such as the public-private partnership (PPP) under the International Hydrogen Ramp-up Programme (H2Uppp), international funds and to suitable technology partners from Germany and elsewhere.

The project analyses industry segments that would be suitable for pilot projects and facilitates contact with German/European companies. Additional training sessions raise awareness among local hydrogen consumers, producers and project developers with the involvement of German solution providers. Local companies gain access to suppliers, who are made aware of specific opportunities. Due to their pioneering role, they may profit from financial support measures for pilot projects.

The project is thus supporting the energy transition in the partner countries. At the same time, German and European companies can benefit from this approach as it supports the better understanding of markets and the study project opportunities whilst strategic contacts are also acquired in developing countries and emerging economies.

The series of sector analyses available explore the green hydrogen market potential of Ghana, Kenya, Jordan, and Vietnam and can be downloaded from GIZ's H2-PDP project website: Changing from grey to green hydrogen production – giz.de

Executive summary

Why start a hydrogen business in Jordan?

The objective of this sector analysis is to provide German and European business with an overview of the hydrogen (H_2) market in Jordan. It aims to offer simplified cost estimations and orientations for establishing a new business in the country. This report targets companies seeking partnerships with local entities that utilise hydrogen as the primary feedstock for their industrial processes. Jordan presents numerous opportunities for international investors, including political and economic stability, abundant solar and wind resources and a strong commitment from the government to develop new energy sources and diversify the energy mix.

Establishing a business in Jordan brings several advantages, such as forming partnerships with local companies and creating decarbonised solutions for industries by leveraging the country's renewable resources, particularly wind and solar energy. This enables the production of affordable and carbon-free energy for green hydrogen generation. Producing hydrogen locally serves as an attractive alternative to reduce the country's reliance on imported fossil-based hydrogen commodities and enhance energy independence. Furthermore, the market prospects for green hydrogen are expected to grow as electrolysis technology costs decline and the demand for decarbonised products increases among customers willing to pay a premium.

Green hydrogen and ammonia opportunities

Green hydrogen and its derivatives offer multiple benefits such as the decarbonisation of processes and end products, energy storage, renewable energy integration, energy security and economic opportunities. These technologies can play an essential role in the transition to a sustainable and low-carbon economy. The analysis explains green hydrogen and ammonia production processes, input product requirements and associated costs in detail. Additionally, a brief overview describing the import and export balance of hydrogen-based commodities in the country is provided. Furthermore, the local industries with the highest potential for transitioning to green hydrogen applications are also highlighted.

Zusammenfassung

Warum sollte man ein Wasserstoffprojekt in Jordanien starten?

Diese Sektoranalyse skizziert, welche Perspektiven der Wasserstoffmarkt in Jordanien deutschen und europäischen Unternehmen bietet. Sie liefert vereinfachte Kostenschätzungen für die Herstellung von grünem Wasserstoff mit Photovoltaik (PV) und Orientierungshilfen für die Umsetzung eines Projekts in Jordanien. Dieser Bericht wendet sich an deutsche und europäische Firmen mit Interesse an einer Partnerschaft mit jordanischen Unternehmen, die Wasserstoff als Hauptrohstoff für ihre industriellen Prozesse nutzen. Jordanien bietet internationalen Investor*innen gute Voraussetzungen wie zum Beispiel politische und wirtschaftliche Stabilität, reiche Solar- und Windressourcen und ein starkes Engagement der Regierung für die Entwicklung neuer Energiequellen und die Diversifizierung des Energiemixes.

Ein Projekt in Jordanien ermöglicht den Aufbau von Partnerschaften mit lokalen Unternehmen, sowie die Entwicklung kohlenstoffarmer Lösungen für die Industrie mittels erneuerbarer Energien, vor allem Wind- und Solarkraft. Die erschwingliche und kohlenstofffreie Energie lässt sich für die Erzeugung von grünem Wasserstoff nutzen. Die lokale Produktion von Wasserstoff ist eine attraktive Alternative, um die Abhängigkeit des Landes von fossilen Rohstoffen zu verringern und die Energieunabhängigkeit zu verbessern. Darüber hinaus dürften die Marktaussichten für grünen Wasserstoff steigen, da die Technologiekosten für die Elektrolyse sinken und immer mehr Kund*innen bereit sind, einen Aufpreis für kohlenstofffreie Produkte zu zahlen.

Chancen für grünen Wasserstoff und Ammoniak

Grüner Wasserstoff und seine chemischen Derivate bieten zahlreiche Vorteile, darunter die Dekarbonisierung von Prozessen und Produkten, Energiespeicherung, Integration erneuerbarer Energien, Energiesicherheit und neue wirtschaftliche Chancen. Diese Technologien können eine wesentliche Rolle beim Übergang zu einer nachhaltigen und kohlenstoffarmen Wirtschaft spielen. Die Analyse erläutert im Detail die Verfahren zur Herstellung von grünem Wasserstoff und grünem Ammoniak, die Anforderungen an die Ausgangsprodukte und die damit verbundenen Kosten. Darüber hinaus wird ein kurzer Überblick über die Import- und Exportbilanz von Wasserstoffgütern in Jordanien gegeben. Die Analyse nennt zudem die lokalen Industrien mit dem größten Potenzial für den Übergang zu grünen Wasserstoffanwendungen.

Benefiting from Jordan's solar energy sources to produce green hydrogen

Jordan possesses abundant renewable energy resources, especially solar, which could be used to produce renewable hydrogen. The specific focus is put on green hydrogen produced from solar photovoltaics (PV) with cost details presented in the case studies. Interviews with local manufacturers in Jordan supplemented by informal discussions and a detailed sector analysis were conducted to gauge potential interest in producing their own green hydrogen. Business cases were developed based on the interviews and represent typical sector scenarios for replacing grey hydrogen with green hydrogen. The business cases focus on current grey hydrogen consumers, where hydrogen is either a production feedstock or an element in the current manufacturing process. The analysis estimates the system sizing, cost including the electrolyser system and solar PV plant, as well as calculating the levelised cost of hydrogen (LCoH) given the local solar resource. Two business cases are presented for illustrative purposes, in which green hydrogen is used for green ammonia and food production.

Establishing hydrogen policies to support investments

The country primarily relies on fossil fuel imports to meet its energy needs and actively seeks to diversify its energy mix. Clean hydrogen production could be one of the solutions that will help to transform the industrial sector and strengthen its economy. Jordan's renewable policies: the Renewable Energy and Energy Efficiency Law introduced in 2021 and the country's Master Strategy for the Energy Sector 2020 – 2030 (update of the 2007 – 2020 strategy) proved to be a successful tool that increased the current share of renewables from almost non-existent to 19 %. The government of Jordan is currently considering options and opportunities for implementing green hydrogen as part of the plan to increase energy security and reliability as well as maximise the utilisation of renewable energy.

Nutzung der jordanischen Solarenergie zur Herstellung von grünem Wasserstoff

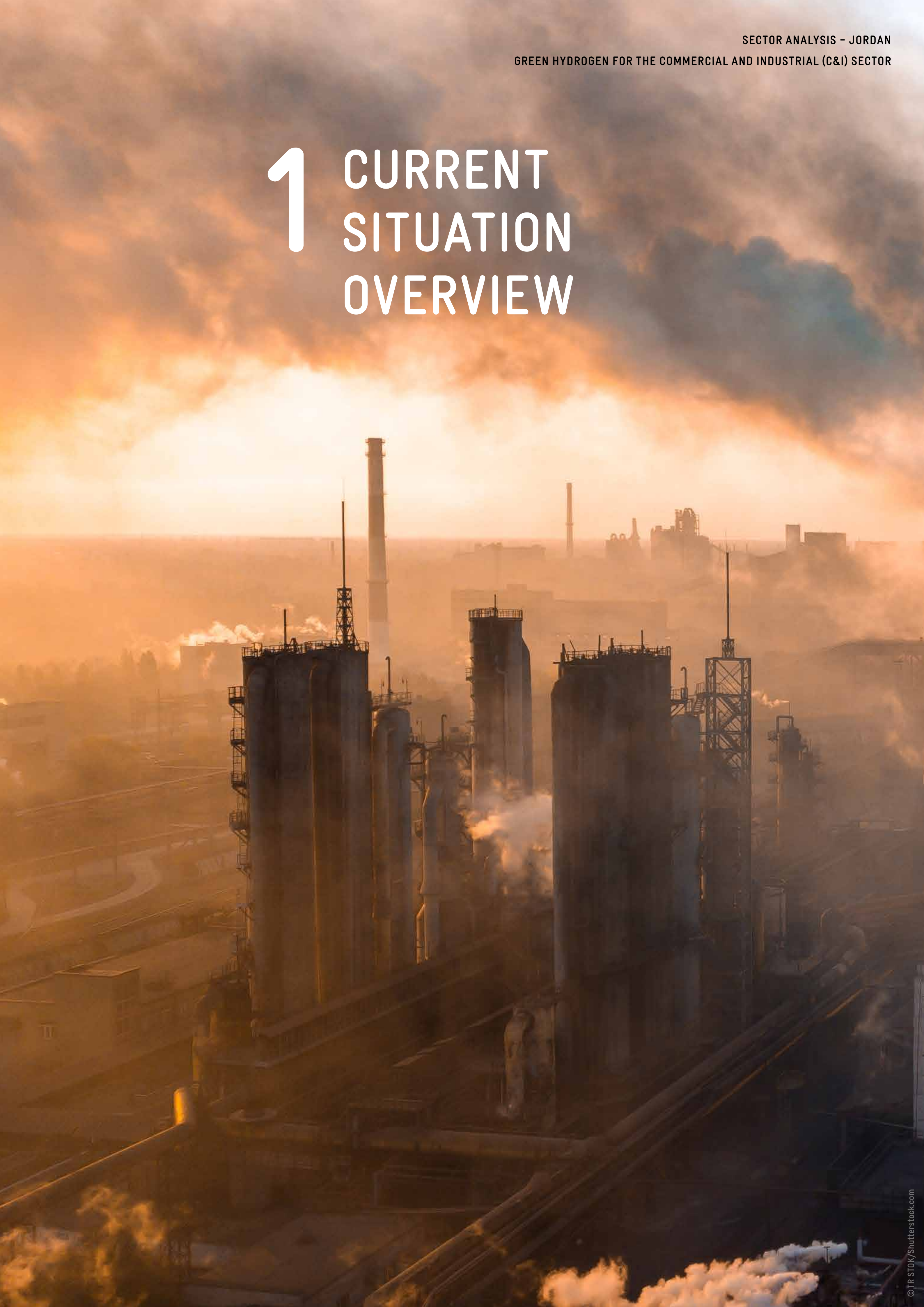
Jordanien ist reich an erneuerbaren Energieressourcen. Vor allem die Solarkraft könnte zur Herstellung von erneuerbarem Wasserstoff genutzt werden. Ein Schwerpunkt liegt deshalb auf erneuerbarem Wasserstoff, der mit Solarenergie gewonnen wird. Die entsprechenden Kosten werden in den Fallstudien dargestellt. Interviews mit lokalen Hersteller*innen, informelle Gespräche und eine detaillierte Sektoranalyse geben Aufschluss über das Interesse an der Produktion von grünem Wasserstoff. Auf der Grundlage der Interviews wurden Geschäftsszenarien entwickelt. Sie stellen typische Branchenszenarien für den Ersatz von grauem durch grünen Wasserstoff dar. Die Szenarien konzentrierten sich auf die derzeitigen Verbraucher von grauem Wasserstoff, bei denen Wasserstoff entweder ein Produktionsrohstoff oder ein Element im Herstellungsprozess ist. Die Analyse liefert eine Einschätzung der Systemkosten, der Kosten für das Elektrolyseursystem und die Photovoltaikanlage sowie die nivellierten Wasserstoffkosten (LCoH) in Abhängigkeit von den lokalen Solarressourcen. Zwei Fallbeispiele machen die Nutzung von grünem Wasserstoff für die Herstellung von grünem Ammoniak und Lebensmitteln anschaulich.

Einführung einer Wasserstoffpolitik zur Förderung von Investitionen

Jordanien deckt seinen Energiebedarf derzeit hauptsächlich mit importierten fossilen Rohstoffen und bemüht sich, seinen Energiemix zu diversifizieren. Die Produktion von sauberem Wasserstoff könnte eine der Lösungen sein, die zur Umgestaltung des Industriesektors und zur Stärkung der Wirtschaft des Landes beitragen.

In der Politik Jordaniens zur Förderung erneuerbarer Energien haben sich das Gesetz für erneuerbare Energien und Energieeffizienz von 2021 und die Master-Strategie für den Energiesektor 2020 – 2030 (Aktualisierung der Strategie 2007 – 2020) als erfolgreich erwiesen. Mithilfe der Gesetze konnte der Anteil der erneuerbaren Energien von fast null auf derzeit 19 Prozent gesteigert werden. Die jordanische Regierung prüft aktuell Optionen zur Einführung von grünem Wasserstoff als Teil des Plans zur Verbesserung der Energiesicherheit und -zuverlässigkeit sowie zur Maximierung der Nutzung erneuerbarer Energien.

1 CURRENT SITUATION OVERVIEW



1. Current Situation Overview

Hydrogen is a promising energy carrier which has the potential to play a significant role in Jordan's energy mix diversification and low carbon transition. The country relies on fossil fuel imports to meet its energy needs due to the lack of significant domestic fossil sources. Rapid economic development, population growth and the development of new industrial sectors as well as the expansion of existing industrial sectors have put additional strain on the energy system. Jordan needs additional sources of energy, and clean hydrogen production could be one of the solutions that will help to transform the energy sector and strengthen its economy.

Jordan has a comprehensive regulatory framework for renewable energy implementation, governed by the Renewable Energy and Energy Efficiency Law introduced in 2021, which provides incentives for private sector investment in renewable energy, addressing various aspects of project development, connection and remuneration. The country's Master Strategy for the Energy Sector 2020-2030, developed by the Ministry of Energy and Mineral Resources (MEMR), aims to achieve a sustainable future energy supply through diversification of the national energy mix, increased reliance on domestic energy resources, enhanced energy security and reduced dependence on costly electricity supply. The strategy sets targets of 31% of the renewable energy share in total power generation capacity and 14% in the overall energy mix by 2030. In 2021, solar and wind accounted for around 19% of the country's generation, which is a significant improvement compared to previous years where the renewables sector was almost non-existent, and proves that well-structured policies could create a significant impact in driving the country's energy transformation.

While the hydrogen sector in Jordan is still in its early stages of development, the country has taken proactive measures to explore its potential as a clean energy source and align it with its energy and climate policies. The primary motivation behind adopting green hydrogen is to diversify the country's energy mix while leveraging its abundant solar and wind resources. The chemical (fertilisers), refining and steel industries are identified as the most promising sectors for utilising green hydrogen and its derivatives. Implementing on-site green hydrogen production would yield several advantages for these industries, including reduced dependence on imports and the mitigation of risks associated with commodity prices, reliability and accessibility.

1.1 Assessment of the energy landscape

The Hashemite Kingdom of Jordan has limited fossil fuel resources; however, the energy system is dominated by fossil fuel generation. This causes serious concern in terms of energy security and long-term cost of supply (imported natural gas). Therefore, in the Master Strategy for the Energy Sector 2020-2030, the MEMR aims to increase the share of domestic energy resources in the primary energy mix to 48.5%. This is to be accomplished primarily through increasing renewable energy (RE) to 31% of the total installed capacity (3,200 MW) by 2030, as well as utilising locally available oil shale.

The electricity sector in Jordan is unbundled with private participation in the generation sector, especially for renewable energy. The National Electric Power Company (NEPCO) is the state-owned, single electricity buyer and seller, also managing the transmission network cross-border sales, as well as the single importer of Liquefied Natural Gas (LNG), managing pipeline as well as oil and gas generation (NEPCO, 2021).

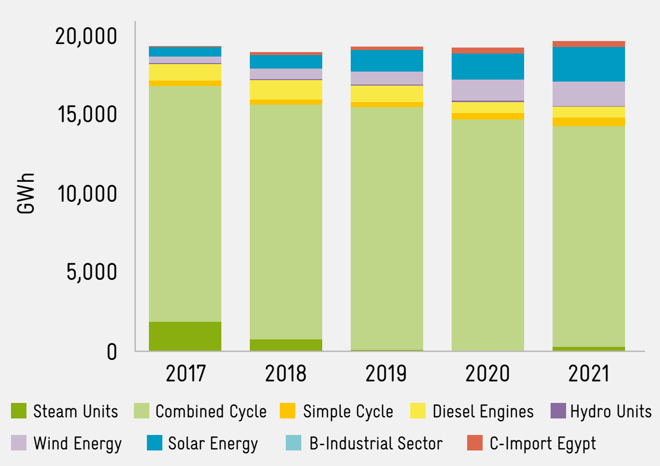
1.1.1 Electricity generation

Jordan has limited domestic fossil fuel resources and is heavily dependent on fuel imports as the energy system is dominated by natural gas combined-cycle power plants. To diversify the energy supply and reduce reliance on imported natural gas, Jordan is investing significantly in renewable energy.

As of 2021, there was 5.5 GW of generation capacity (sold to electricity companies) in the Jordanian system, nearly 1.6 GW of which was solar and wind, up from 1.4 GW in 2020 (NEPCO, 2021). In addition, there is a significant amount of captive renewable energy capacity in Jordan. According to the Director of Planning and Institutional Development at the Ministry of Energy and Mineral Resources, Shorouk Abdel Ghani, 2,445 MW of renewable energy capacity was installed in 2021, of which electrical energy from 1,498 MW systems was sold to electricity companies and a further 947.6 MW was captive capacity from non-commercial systems (Jordan Times, 2022).

Jordan has also experienced a rapid increase in terms of renewable energy production, increasing from 125 GWh in 2015 to 3,758 GWh in 2021. Solar and wind accounted for around 19% of total electricity production in 2021 (NEPCO, 2021).

FIGURE 1. HISTORICAL ELECTRICAL ENERGY BY GENERATION SOURCE IN JORDAN

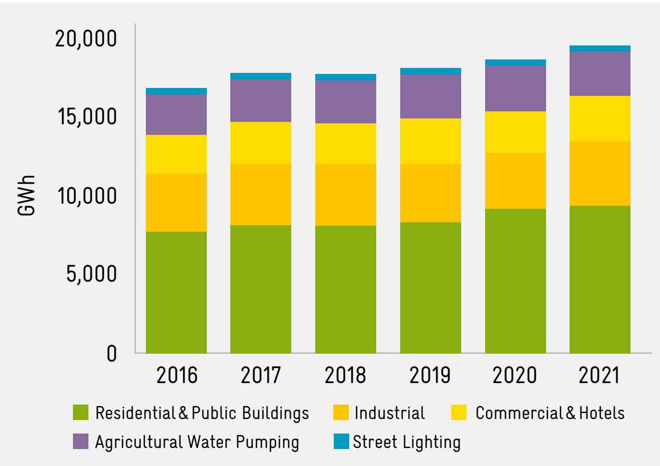


Source: Authors' own illustration, ENGIE Impact GmbH (2023), based on [(NEPCO, 2021)]

1.1.2 Electricity demand composition

According to the MEMR, in 2021 residential and public buildings accounted for around 48% of Jordan's electrical demand, industrial sectors 21% and commercial and hotels around 14%.

FIGURE 2. HISTORICAL ELECTRICAL CONSUMPTION BY CLIENT TYPE



Source: Authors' own illustration, ENGIE Impact GmbH (2023), based on (MEMR, 2022)

The Energy Strategy to 2030 estimates future demand growth increasing to 19,701 GWh by 2030. The following table presents the forecasted electricity demand. There is no available distribution of future electricity consumption by client type.

TABLE 1. FORECASTED ELECTRICITY DEMAND TO 2030

Year	Electricity Demand (GWh)	% Increase
2020	17,672	
2021	17,831	0.90%
2022	17,860	0.16%
2023	17,950	0.50%
2024	17,958	0.04%
2025	18,686	4.05%
2030	19,701	5.43%

Source: Authors' calculation, ENGIE Impact GmbH (2023), based on (MEMR, 2020)

1.2 Energy prices

1.2.1 Electricity prices

Retail electricity tariffs are set by the Energy and Minerals Regulatory Commission (EMRC) and vary depending on type of user (residential, commercial, small industry, medium industry, agriculture or electric vehicle charging), time of use and volume consumed. The industrial tariff ranges from JOD 0.060/kWh – JOD 0.068/kWh (EUR 0.84/kWh – EUR 0.96/kWh) and residential rates range from JOD 0.050/kWh to JOD 0.200/kWh (EUR 0.070/kWh – EUR 0.28/kWh) (JEPCo, 2022). See Table 17 in the Appendix for the complete tariff schedule.

1.2.2 Gas prices

Local fuel prices are published by the MEMR monthly. A selection of November 2022 prices are shown in the table below.

TABLE 2. 2023 FUEL PRICES

Fuel Prices November 2023				
Diesel	Fils/Litre	715	EUR/Litre	0.92
LPG (12.5 kg)	JD/Cylinder	7	EUR/Cylinder	9.04
LPG (50 kg)	JD/Cylinder	36.34	EUR/Cylinder	46.91
LPG (Bulk for Central Distribution)	JD/Ton	675.62	EUR/Ton	872.11
Natural Gas (Industry)	JD/MMBTU	4.814	EUR/MMBTU	6.21
Fuel Oil (Bunker)	JD/Ton	394.42	EUR/Ton	509.13
Diesel (Bunker)	Fils/Litre	715	EUR/Litre	0.92

Source: Authors' representation based on (MEMR, 2023), exchange rate EUR 1 = JOD 0.7747

The Jordanian government has encouraged industrial users to switch from oil to natural gas through a NEPCO agreement to provide natural gas to certain industrial complexes and through the reduction of the special tax on natural gas to industries being reduced from 16% to 7%. In addition, companies that switch to natural gas are exempt from the special tax imposed on natural gas for three years, according to criteria set by the Ministry of Industry (IRENA, 2021).

1.3 Legislative and regulatory framework

Jordan has an extensive regulatory framework with respect to the implementation of renewable energy. The development of the renewable energy sector in Jordan is governed by the Renewable Energy and Energy Efficiency Law and its amendments adopted in 2012, supporting bylaws and directives. Key examples are:

- Bylaw No. 50 of 2015 (amended in 2016) on the conditions and procedures for renewable energy direct proposal submission and connection to the grid.
- Instructions relating to the Renewable Energy and Energy Efficiency Law Article 10/B (net-metering system) regarding the sale of renewable energy.
- Instructions and costs related to electricity wheeling of RE for captive consumption.
- Bylaw No. 10 of 2013, last amended in 2018, on tax exemptions for RE and energy efficiency systems and equipment.

1.3.1 Renewable energy incentive mechanisms

This extensive regulatory framework has enabled the implementation of significant levels of new RE capacity in recent years. Renewable energy projects can be implemented via one of several pathways:

- Direct proposal scheme (BOO competitive bidding), where MEMR contracts for specified capacity and developers propose projects they have identified and will develop. Projects are awarded through a two-stage bidding process. These bids are subject to a ceiling price set by the EMRC as set forth in Bylaw No. 50/2015.
- Government-sponsored Engineering Procurement & Construction (EPC) turnkey projects.
- Self-consumption (wheeling and net metering), where consumers can sell excess renewable energy (RE) produced power at fixed prices (instructions issues by the EMRC).
- The government of Jordan has implemented several incentive mechanisms to encourage the implementation of renewable energy as summarised in the table below.

TABLE 3. SUMMARY OF RENEWABLE ENERGY POLICY INSTRUMENTS

RE Policy Instruments	Description
Mechanisms to support renewable energy	Direct proposal with competitive bidding Net-metering scheme (for self-consumption)
Investment support	Jordan Renewable Energy & Energy Efficiency Fund (JREEEF) financial (for residential) and administrative support in the implementation of renewable energy
Import tax	Duties and tax exemptions on all locally manufactured and imported renewable energy source equipment and systems

Source: Authors' own illustration, ENGIE Impact GmbH (2023)

There are currently no hydrogen or green hydrogen-related incentive mechanisms in Jordan.

1.4 Pilot projects and enabling infrastructure

The government of Jordan is currently considering options and opportunities for implementing green hydrogen as part of the overall plan to increase energy security and reliability as well as maximise utilisation of renewable energy. To this end, several studies are currently being carried out or have recently been completed including “POWER-TO-[X] Green Hydrogen Opportunities in Jordan” published by Friedrich-Ebert-Stiftung (FES).

A couple of green hydrogen pilot projects have been announced:

- Fortescue Future Industries Pty Ltd (FFI) has signed a memorandum of understanding (MoU) with the government of Jordan (Minister of Environment Dr Muawieh Khalid Radaideh) to study green hydrogen and green ammonia production through large-scale wind and solar energy facilities. The framework agreement provides FFI with a minimum initial area of land for preliminary studies comprising 450 square kilometres for potential solar production, 1,000 square kilometres for potential wind energy production and 1.5 square kilometres within an industrial zone for potential downstream production facilities (Fortscue, 2021).

- An MoU was signed by Jordan (Ministry of Energy and Mineral Resources) and Danish company Moller-Maersk with the objective of developing the production facilities for green marine fuel production. Maersk is one of the largest shipping companies and will conduct a technical and economic feasibility study for further investment in the Aqaba region using desalinated water and renewable energy (Sundar, 2022).

Existing natural gas pipelines could potentially be used for the transport of H_2, either by converting them into a 100% H_2-compatible pipeline or by mixing H_2 with natural gas. While the latter could enable short-term use of the existing infrastructure, it requires the technical compatibility of the pipeline network (i.e. mechanical equipment, material integrity, safety limitations) and downstream consumers to be able operate using the H_2 admixture. Currently, gas transmission pipelines are compatible for H_2 admixtures of up to 10 % of injected gas volume (Deutschen Verein des Gas- und Wasserfaches e. V. , 2014) while sensitive consumers such as gas engines and turbines may have a more limited H_2 content of 1–5% of total volume of gas burnt. In addition to technical compatibility, further aspects such as the reduction of the maximum transport capacity compared to natural gas should be considered.

2 GREEN HYDROGEN TECHNOLOGY AND ESTIMATION OF COSTS IN THE JORDANIAN CONTEXT

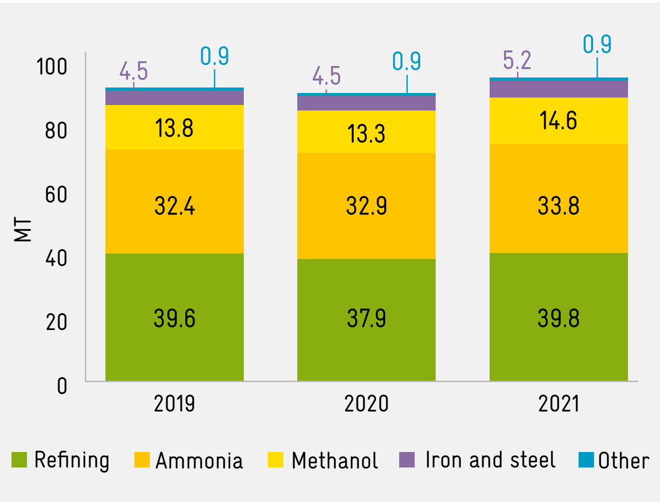
2. Green hydrogen technology and estimation of costs in the Jordanian context

2.1 Introduction to hydrogen-based products

Hydrogen is the most abundant element on earth and an important chemical building block for numerous production processes, including the refining of petrochemicals, industrial processes such as glass and semi-conductor production and in food production. Hydrogen is also a feedstock used in the production of downstream products such as ammonia and methanol.

Hydrogen has been produced on a significant industrial scale for decades. Currently, 95% of global hydrogen is produced using fossil fuels (grey hydrogen) (IRENA, 2018), primarily through the natural gas-based steam reforming process which is used to produce around 69 million tons of hydrogen annually (Statista). For the production of hydrogen, a typical natural gas-based steam reforming plant with 607 t/d capacity results in a H_2 production cost of USD 1.22/kg, depending on natural gas prices (A.O. Oni, 2022). The primary drawback to this process are the significant carbon dioxide (CO_2) emissions, which range on average between 8-9 kg CO_2/kg H_2. Global demand for hydrogen in 2021 was 94 Mt, a 5% increase compared to 2020 (IEA, 2022).

FIGURE 3. HYDROGEN DEMAND BY SECTOR



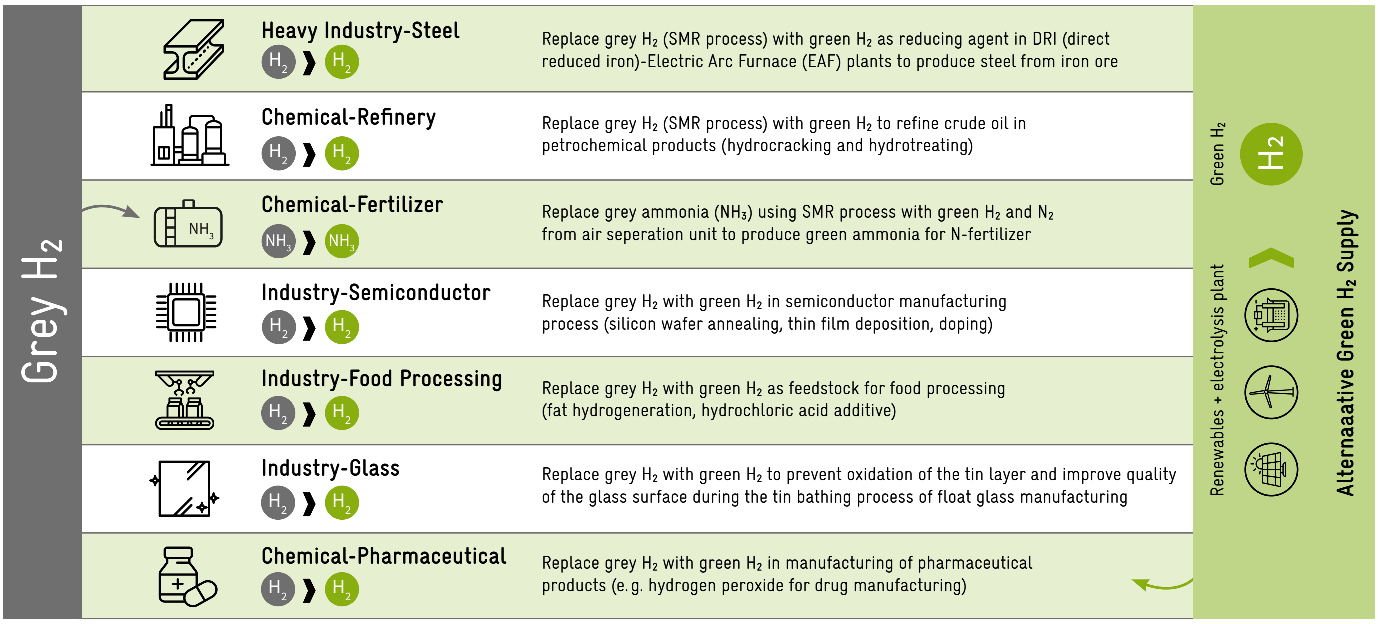
Source: Authors' own illustration, ENGIE Impact GmbH (2023), based on (IEA, 2022)

Hydrogen is predominantly used in refining as well as in the production of downstream products such as ammonia and methanol. Only about 6% of hydrogen produced is used for pure hydrogen demand (IEA, 2019). This share of hydrogen goes into the manufacturing processes of a wide variety of petrochemical products (PU foams, oxo-alcohols, nylon, etc.), pharmaceuticals, food production, electronics, etc. Hydrogen is mainly produced on-demand and on-site for treatment purposes or the production of chemicals.

In the context of the decarbonisation of industrial processes, green hydrogen is one of the favoured commodities. There are several utilisation routes for green hydrogen. One is the replacement of fossil-based hydrogen in synthesis or treatment processes. It is also used as a reduction gas, for example, in the steel industry. Another is the replacement of fossil energy sources for heating purposes, as well as an energy carrier for electrical storage purposes.

Numerous sectors currently use hydrogen (or hydrogen-based products) as part of their production processes. These include heavy industry, for example, in steel production, in the chemical sector in refineries, for fertiliser production and pharmaceuticals, and in the industrial sector, for example, in float glass, semiconductor or food production. Figure 4 shows a selection of current industrial uses of hydrogen and how these can be replaced with carbon-free green hydrogen alternatives.

FIGURE 4. CURRENT INDUSTRIAL USES OF GREY HYDROGEN



Source: Authors' own illustration, ENGIE Impact GmbH (2023)

As described above, hydrogen is extremely versatile and green hydrogen unlocks new possibilities for industry decarbonisation as well as contributing to energy security. However, hydrogen is a gas under atmospheric conditions and therefore needs to be processed either through compression or conversion to make it suitable for transport. The most attractive options for shipping hydrogen are ammonia, liquid hydrogen and liquid organic hydrogen carriers (LOHC) (Blanco, 2022).

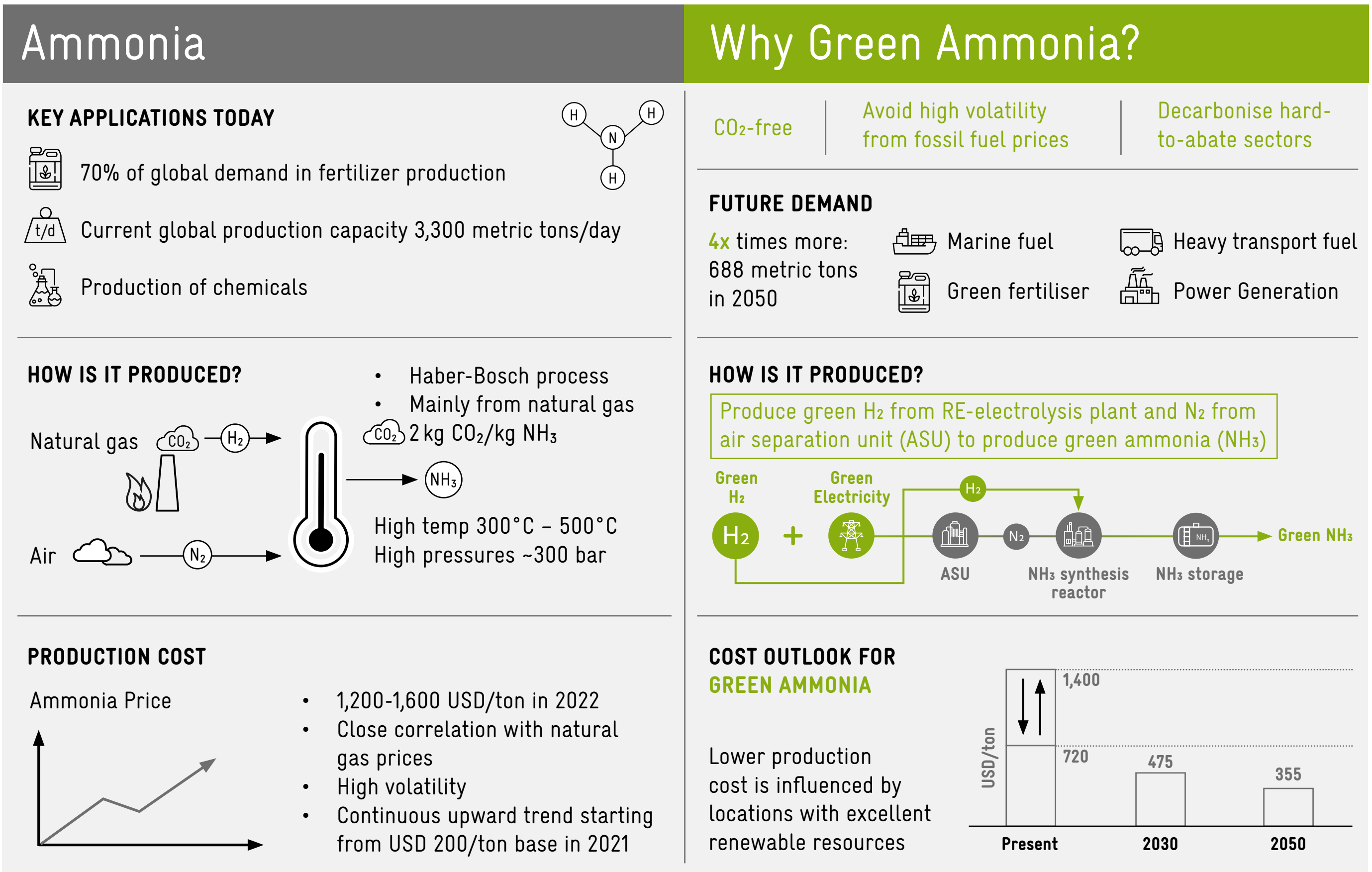
2.2 Hydrogen downstream products

The two primary downstream hydrogen-based products are methanol and ammonia. Methanol is a highly versatile commodity which is used as a fuel and in the production of plastics, silicone, acetic acid and formaldehyde, among others. Ammonia is primarily used as a chemical to create fertilisers, including urea and diammonium phosphate (DAP).

2.2.1 Ammonia

Ammonia (NH_3) is the largest hydrogen-based downstream chemical by volume, representing around 43% of global hydrogen demand, with around 236 million tons produced worldwide in 2021 (Statista, 2022). It is the primary feedstock for nitrogen fertilisers, which account for around 70% of global ammonia demand. The production of NH_3 is a chemical synthesis process which requires H_2 and nitrogen (N_2), at a ratio of 18% H_2 and 82% N_2 as feedstock. As most of the current ammonia production is dependent on natural gas, ammonia prices are strongly correlated to those of natural gas. Conventional ammonia production is an emission-intensive process as it primarily relies on fossil fuels, with over 70% of production using natural gas and the remaining 30% using coal. This most common fossil fuel-based Haber-Bosch process emits CO_2 in the order of 2 kg per kg of ammonia (Ghavam, 2021). Switching to green ammonia can significantly reduce greenhouse gas emissions in agriculture and transportation as it could be used as carbon-free fuel or fertiliser.

FIGURE 5. GREY AND GREEN AMMONIA PROPERTIES

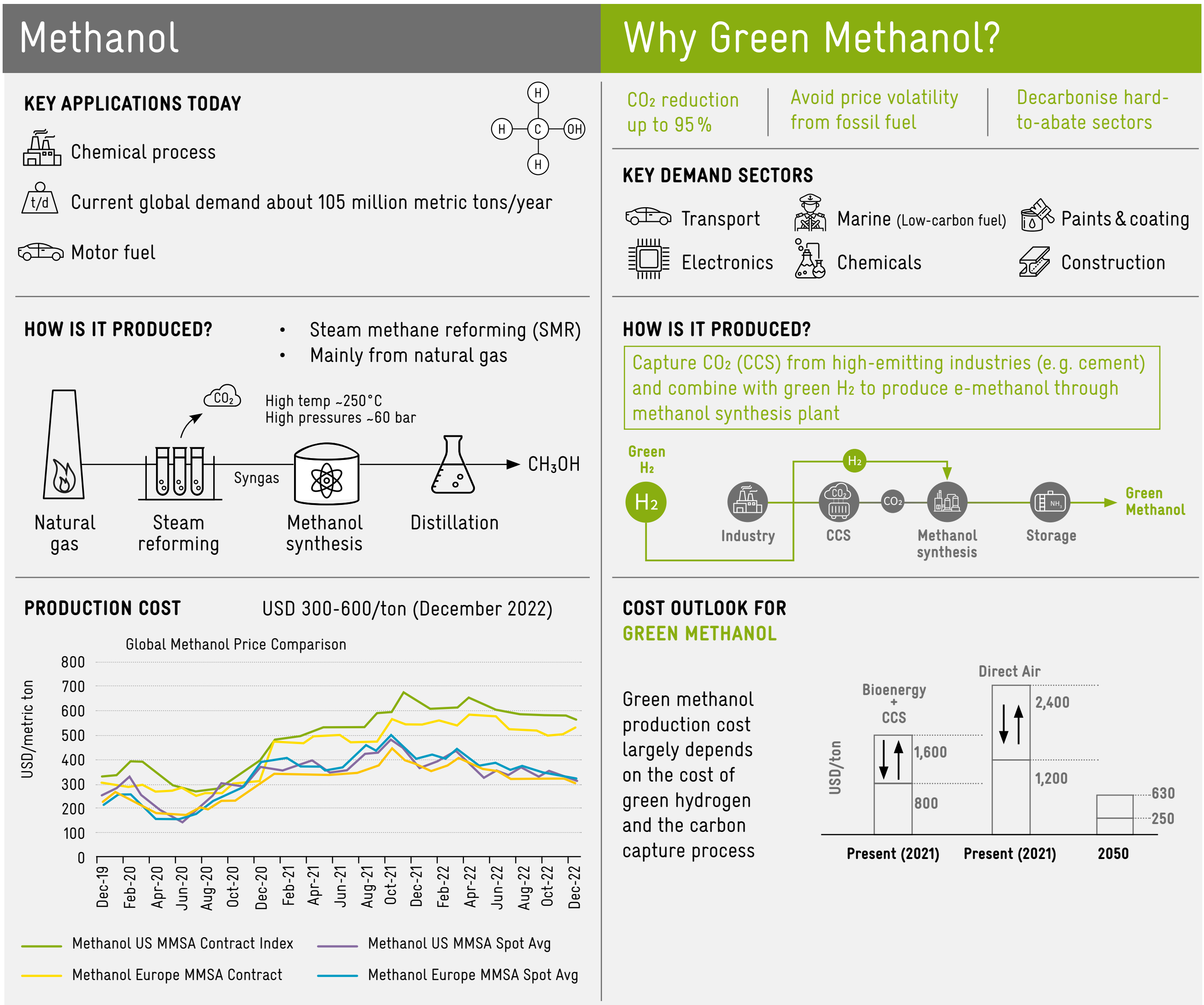


Source: Authors' own illustration, ENGIE Impact GmbH (2023), based on (Fasihi, M. et al., 2021) and data from Bloomberg

2.2.2 Methanol

Methanol (CH_3OH) is a simple water-soluble alcohol which can be used as a fuel for combustion engines or in methanol fuel cells, as a solvent, an anti-freeze, and a base chemical in the production of various downstream chemicals such as polymers, formaldehyde and acetic acid. The predominant methanol consumer is the automotive sector where it is mainly used as a motor fuel offering multiple advantages due to its high-octane content, which improves engine efficiency. Methanol is typically produced through the process of catalytic reduction of carbon monoxide (CO) with H_2, called syngas, with a catalyst used at high pressures (up to 60 bar) and high temperatures (about 250°C), in a process known as „methanol synthesis". Green methanol is gaining significant interest as its production methods could cut up to 95% of CO_2 emissions compared to traditional methods (Methanol Institute, 2021).

FIGURE 6. GREY AND GREEN METHANOL PROPERTIES



Source: Authors' own illustration, ENGIE Impact GmbH (2023), based on (Methanol Institute, 2023) and (IRENA, 2021)

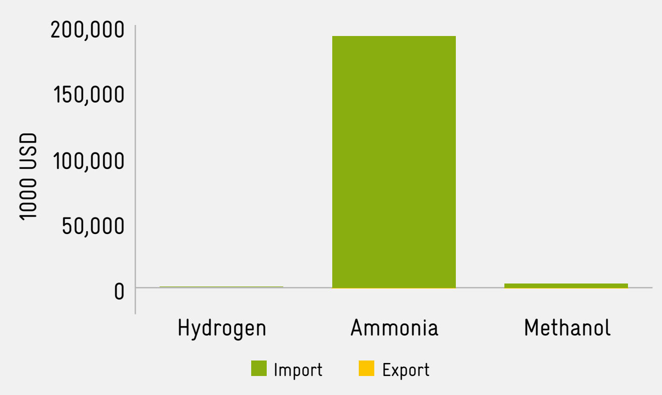
2.3 Industrial use of hydrogen in Jordan

The main hydrogen-consuming industries in Jordan are the refinery and fertiliser sectors. Jordan primarily imports ammonia as a feedstock for chemical (fertiliser) production through the port of Aqaba, with limited domestic production. Key sectors currently using grey hydrogen are:

- Chemical – fertilisers. There are 13 fertiliser companies in Jordan. The H_2 and ammonia consumption quantities for fertilisers are not available in the public domain.
- Industry – food. There are 5 vegetable oil and margarine manufacturing companies. The H_2 consumption quantities for the food sector are not available in the public domain.
- Chemical – pharmaceutical. Jordan has 15 pharmaceutical manufacturers; however, no public information is available on H_2 volumes.
- Chemical – refinery. Jordan Petroleum Refinery Company owns and operates the only refinery in Jordan. The refinery site is located in the city of Zarqa around 35 km east of the capital Amman. The existing refinery in Zarqa has a production capacity of 60,000 barrels per day (bpd). H_2 is used within the refining process for fuel processing purposes (for hydrotreating and hydrocracking). The H_2 consumption quantities for the crude oil refinery are not available in the public domain.

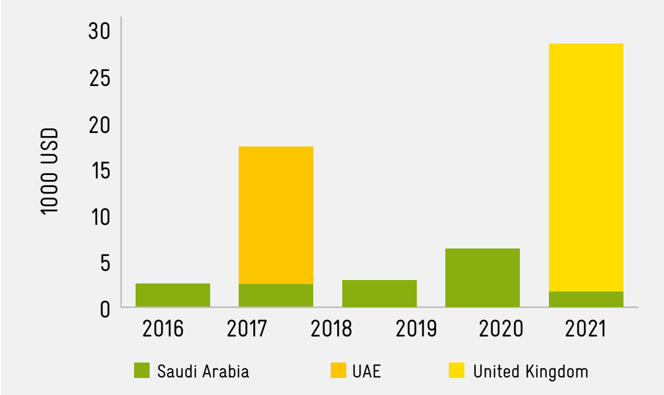
Jordan imports about USD 11 k of hydrogen per year; this is equivalent to an estimated, approximate, 3 ton/year with a growth trend over the last 3 years (World Bank, 2022). Most significantly, the country is a net importer of ammonia of around USD 65,000 k p.a., amounting to 165,000 tons of imports per annum with a clear growth trend. Ammonia imports account for almost 98% of all hydrogen and hydrogen-based imported feedstock. Jordan is an importer of methanol, primarily from Saudi Arabia, with an annual volume of around 1,765 tons, amounting to about USD 736,000 k p.a. (World Bank, 2022).

FIGURE 7. JORDAN'S TRADE BALANCE BY FEEDSTOCK IN 2017–2021



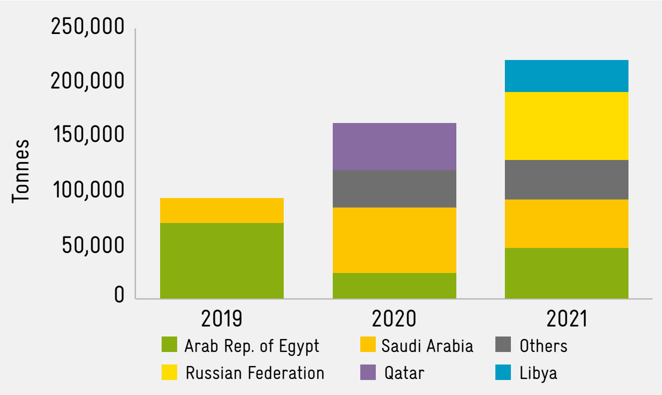
Source: Authors' own illustration, ENGIE Impact GmbH (2023), based on (World Bank, 2022)

FIGURE 8. JORDAN'S HYDROGEN IMPORTS BY COUNTERPARTY



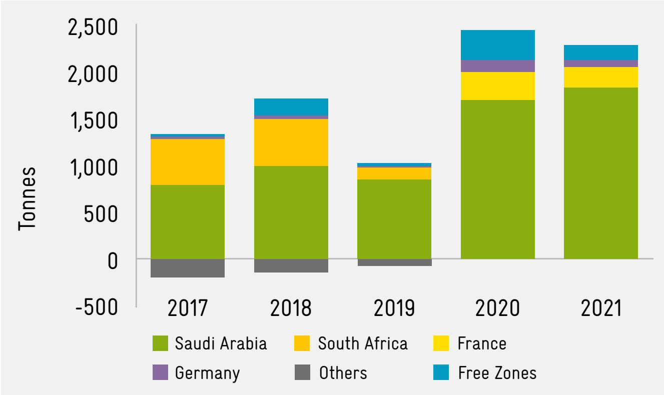
Source: Authors' own illustration, ENGIE Impact GmbH (2023), based on (World Bank, 2022)

FIGURE 9. AMMONIA IMPORTS TO JORDAN BY COUNTERPARTY 2019–2021



Source: Authors' own illustration, ENGIE Impact GmbH (2023), based on (World Bank, 2022)

FIGURE 10. METHANOL IMPORTS AND EXPORTS TO AND FROM JORDAN BY COUNTERPARTY 2017–2020



Source: Authors' own illustration, ENGIE Impact GmbH (2023), based on (World Bank, 2022)

Jordan relies on fossil fuel imports to meet its energy needs. In 2018, the country imported around 92% of its primary energy, which creates multiple risks in terms of price, reliability and accessibility of supplied commodities (IRENA, 2021). The Kingdom has established the necessary policies and incentive mechanisms to support the growth of renewables in the energy mix with great success. In 2021, the share of solar and wind in the country's energy generation accounted for around 19%, which is a significant improvement compared to previous years where the renewables sector was almost non-existent. The country urgently needs new sources of energy; clean hydrogen production could be one of the solutions that will help to transform the sector.

The main imported hydrogen-based products to Jordan are pure hydrogen, ammonia and methanol, with the second accounting for the largest share in terms of volume – representing almost 98% of the total imported value. Key derivative products where ammonia is used are mostly associated with fertiliser production. There are currently 13 fertiliser companies operating in Jordan, demonstrating that there is market potential for local production and deployment of PtX products. Producing green ammonia on-site would bring multiple benefits to the country's economy, including reduced dependency on imports and risks associated with market price fluctuations.

Moreover, developing a green ammonia industry can help diversify a country's economy, increase its resilience to economic shocks and build new clean energy production capacities. Most of the fertiliser plants are located within the vicinity of the port of Aqaba, which is also where the planned Aqaba-Amman Water Desalination and Conveyance Project (AAWDCP) is located. This project creates favourable conditions for the introduction of green ammonia production.

In addition, green ammonia can provide a sustainable source of nitrogen for fertiliser production, which can help meet the demand for fertilisers while reducing the environmental impact. It is noted that the regions with the highest hydrogen-producing potential in Jordan are situated in the southern part of the country and in proximity to the fertiliser plants which can improve energy or hydrogen transportation efficiency.

Jordan has a well-established steel industry with several steel plants and steel re-rolling mills in operation. These often import liquid ammonia for their industrial processes. The demand for steel comes from the domestic construction sector as well as exports to the Middle East and North Africa. The growth pattern is mostly driven by national infrastructure projects and regional construction demand. Introducing green hydrogen and ammonia into steel-making processes could improve overall energy efficiency, reduce emissions and develop local production capacities.

Jordan could benefit from its vast renewable resources, particularly wind and solar potential. According to the import and export balance, methanol represents a very small share of imports to the country, as represented in Figure 7 (World Bank, 2022). This indicates the potential for producing green methanol locally and developing new uses in the transport or chemical sectors. It is difficult to estimate the potential needs at this stage, but adding green methanol as an additive to fossil-based fuels could be an initial step in reducing the country's reliance on fossil fuel imports for transport. Hydrogen-based solutions could also be used as an energy carrier for off-grid supply to isolated grids or individual consumers, serving as pilot schemes.

While pure hydrogen volumes represent the smallest share of imports, there is still potential for Jordan to transition to green hydrogen, particularly in the refining and food industries. Compared to grey hydrogen, green hydrogen improves product quality by providing a more precise and controlled process for food production. For the refining industry, the greatest benefits will come from increased energy security and a lower carbon footprint.

The sectors with the highest potential of implementing hydrogen and hydrogen-derivatives (i.e. ammonia, methanol, etc.) in their processes could be primary located in the middle (Amman) and south (Aqaba) of the country. The following section will provide a more detailed view of the hydrogen processes used in selected key sectors.

2.4 Power-to-X technology

In this analysis, the Power-to-X (PtX) technologies green hydrogen and green ammonia will be considered from a techno-economic perspective as they are best suited to the current conditions in the country.

2.4.1 Green hydrogen production process

In the context of Power-to-X systems, green hydrogen is produced via the electrolysis of water, using electricity and water as inputs to produce hydrogen as the main product. The electrolysis of water is an electrochemical process in which water is electrochemically dissociated into its molecular components – hydrogen and oxygen.

The main inputs for the electrolysis process are pure water – which needs to be supplied in demineralised quality – and electricity – which needs to be supplied as direct current either from a Direct Current (DC) power source or an Alternating Current (AC) power source after conversion. Depending on the electrolyser type, the average pure water demand is 14 litres of water per kg of hydrogen produced. The main product of the electrolysis process is hydrogen in gaseous form. Oxygen and waste heat are produced as by-products, which can be utilised for external applications.

There are different water electrolysis technologies, of which alkaline electrolysis (AEL) and proton exchange membrane (PEM) electrolysis are the currently most mature technologies for low-temperature systems. Other electrolysis technologies include anion exchange membrane (AEM) and high-temperature solid oxide (SOEC) electrolysis which are currently in the prototype (AEM) and demonstration phase (SOEC), respectively.

The electrolysis process itself is dependent on technology and is characterised by different electrochemical and process parameters.

The main hydrogen production process takes place in the electrolysis cell stacks, which are composed of multiple individual cell modules. At plant level, electrolysis plants include various subsystems for the supply of utilities to the cell stacks. These subsystems include, for example, water treatment, gas treatment, cooling, power conversion and distribution as well as instrumentation and control systems.

Electrolysis plants are characterised by a modular design approach, with currently available designs in the range of 1 MW (small-scale) and 100 MW or more (large-scale). Small-scale electrolysis plants can be delivered as turnkey units based on standardised solutions, while large-scale electrolysis plants are developed as project-specific solutions based on predefined subsystems.

TABLE 4. OVERVIEW OF THE MAIN CHEMICAL REACTIONS OF ALKALINE AND PEM ELECTROLYSIS CELLS

Technology	Cathodic reaction (hydrogen evolution reaction)	Charge carrier	Anodic reaction (oxygen evolution reaction)
Alkaline electrolysis	$H_2O + 2e^- \rightarrow H_2 + 2OH^-$	OH^-	$2OH^- \rightarrow 0.5\ O_2 + H_2O + 2e^-$
PEM electrolysis	$2H^+ + 2e^- \rightarrow H_2$	H^+	$H_2O \rightarrow 0.5\ O_2 + 2H^+ + 2e^-$

Source: Authors' own illustration, ENGIE Impact GmbH (2023)

TABLE 5. OVERVIEW OF THE MAIN PERFORMANCE VALUES OF ALKALINE AND PEM ELECTROLYSIS

	Alkaline electrolysis	PEM electrolysis
Stack efficiency range at full load (LHV)	48–50 kWh/kg ~67–70%	48–52 kWh/kg ~64–70%
Operating temperature range	50–80°C	50–80°C
Operating pressure range	0.15–30 barg	0.15–40 barg
Operating range per module	20–100%	10–100%

Source: Authors' own illustration, ENGIE Impact GmbH (2023)

Green ammonia production process

Wind- or solar-based green ammonia production requires the separate production of both hydrogen and nitrogen. Within the scope of this study, hydrogen is generated by electrolysis. Nitrogen is obtained from ambient air and, from a technical point of view, can be produced in three different ways: cryogenic distillation (air separation unit (ASU)), pressure swing adsorption or separation using a membrane process. All processes are commercially viable and primarily require electrical energy. The process of cryogenic distillation has the lowest specific energy consumption. Hydrogen and nitrogen are then introduced downstream into an ammonia synthesis loop. With a starting material ratio of 18% hydrogen weight to 82% nitrogen weight, ammonia is produced by means of catalytic synthesis – also known as Haber-Bosch synthesis – at temperatures between 300°C and 500°C and high pressures of up to 300 bar. Full conversion to ammonia cannot be achieved in a single pass due to the equilibrium conditions of the Haber-Bosch reaction. Consequently, the overall yield of the plant can be increased by implementing a so-called recycling loop to recycle unreacted reactants.

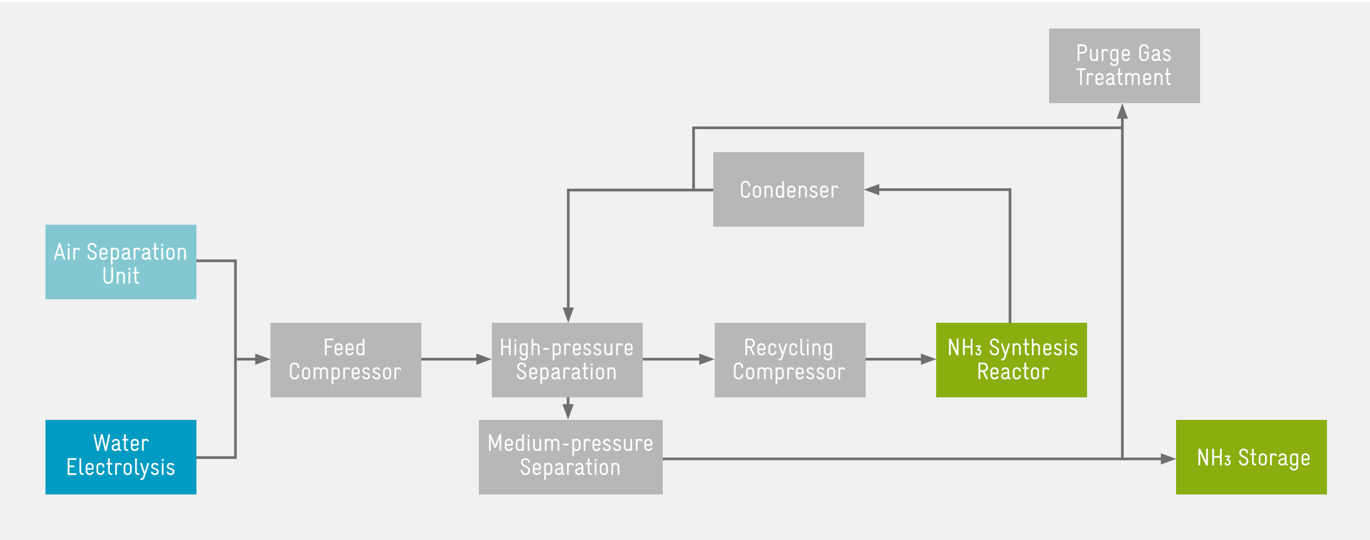
TABLE 6. OVERVIEW OF HABER-BOSCH SYNTHESIS CONDITIONS

Technology	Reaction	Process conditions	Specific consumption for 1 kg NH_3
Haber-Bosch synthesis	1.5 H_2+0.5 $N_2 \leftrightarrow NH_3$	300°C to 500°C up to 300 bar	0.18 kg H_2 0.82 kg N_2

Source: Authors' own illustration, ENGIE Impact GmbH (2023)

During green ammonia production, attention should be paid to ensure that Haber-Bosch synthesis is effected in a constant operating mode when possible. The same applies to cryogenic air separation for the supply of nitrogen. In contrast, PEM electrolysis can be "ramped up or down" under changing current loads. Therefore, when developing the overall process, appropriate compensation of load changes on the upstream side must be taken into account. Consideration should also be given to how constant production quantities can be ensured for the consumer market. The figure below provides an overview of the green ammonia production process.

FIGURE 11. GREEN AMMONIA PROCESS



Source: Authors' own illustration, ENGIE Impact GmbH (2023), based on (EPCM, 2023)

2.5 PtX costs

A set of technical and economic assumptions are defined for the calculation of the levelised cost of hydrogen as well as for the business case calculations, which are summarised in Table 7 and Table 8. The cost assumptions are differentiated between medium- (5 MW) and large-scale (100 MW) system sizes in order to show economies of scale. Note that the capital xxpenditures (CAPEX) assumptions are based on the total installed cost (TIC), including direct costs for equipment supply and indirect costs for plant installation and design.

The technical assumptions are based on average values, common per technology, without differentiation between plant scale.

TABLE 7. TECHNICAL AND ECONOMIC ASSUMPTIONS FOR THE ELECTROLYSIS SYSTEM

		PEM		Alkaline		AEM	SOEC
		Large-scale	Medium-scale	Large-scale	Medium-scale	Small-scale	Small-scale
Spec. CAPEX	EUR/kW	1,300	2,700	840	1,900	4,683	3,650
Spec. fixed OPEX	EUR/kW/year	15	20	20	25	19	32
System efficiency	% LHV	62%	62%	62%	62%	62%	81%
Efficiency degradation	%/year	1.3%	1.3%	1%	1%	1.3%	4%
Stack operational lifetime	hours	65,000	65,000	60,000	60,000	35,000	20,000
Spec. tap water consumption	L/kg H_2	14	14	14	14	14	14
Operating pressure	barg	30	30	0.15	0.15	35	0.15

Source: Authors' own illustration, ENGIE Impact GmbH (2023)

TABLE 8. TECHNICAL ASSUMPTIONS FOR THE HYDROGEN COMPRESSION AND STORAGE SYSTEM

		PEM		Alkaline		AEM	SOEC
		Large-scale	Medium-scale	Large-scale	Medium-scale	Small-scale	Small-scale
Delivery pressure	barg	100	100	100	100	100	100
Spec. compression power	kWh/kg	0.7	0.7	2.8	2.8	0.7	2.8
Max. storage pressure	barg	100	100	100	100	100	100
Max. storage autonomy	hours	72	72	72	72	72	72

Source: Authors' own illustration, ENGIE Impact GmbH (2023)

2.5.1 Green ammonia production costs

The following provides an illustrative example of the cost of green ammonia production when considering a capacity of a 300 tons per day (tpd) ammonia synthesis plant. Table 10 summarises the technical assumptions. Based on the Haber-Bosch reaction, the hypothesis is that a complete conversion of hydrogen and nitrogen into ammonia takes place via the ammonia synthesis cycle. Green hydrogen is produced using PEM electrolysis with a specific consumption of 50 kWh/kg H_2. The total specific consumption for the ammonia synthesis loop, including nitrogen generation, is about 1.2 kWh/kg NH_3. Hence a total of approx. 10 kWh of energy is required to produce 1 kg of NH_3, of which H_2 production is a major component.

TABLE 9. TECHNICAL ASSUMPTIONS FOR GREEN AMMONIA PRODUCTION

Specific Technical Assumptions		
H_2 demand	0.18	kg H_2 /kg NH_3
N_2 demand	0.82	kg N_2 /kg NH_3
PEM electrolysis (50 kWh/kg H_2)	8.8	kWh/kg NH_3
NH_3 synthesis (incl. ASU)	1.2	kWh/kg NH_3
Total energy demand	**10** 36	**kWh/kg NH_3** MJ/kg NH_3

Source: Authors' own illustration, ENGIE Impact GmbH (2023)

Table 10 summarises the capacity and price assumptions. To produce 300 tpd of ammonia, 53 tpd of hydrogen and 247 tpd of nitrogen are required. The production cost calculation considers levelised hydrogen production costs of EUR 8/kg H_2. The energy required for the NH_3 synthesis including ASU is assumed to be provided via grid electricity at EUR 0.16/kWh. As noted previously, due to the cryogenic process, ASU cannot be "ramped up and down" depending on the availability of renewable energy, but must remain relatively constant 24 hours a day. The total investment cost for the NH_3 synthesis loop including the ASU is approx. EUR 82 million.

TABLE 10. GREEN AMMONIA CAPACITY AND PRICING ASSUMPTIONS

Capacity and Pricing Assumptions	
NH_3 capacity	300 tpd NH_3
H_2 demand	53 tpd H_2
N_2 demand	247 tpd N_2
CAPEX NH_3 synthesis (incl. ASU)	EUR 82 m
LCoH	EUR 8/kg
Grid electricity cost	EUR 0.16/kWh

Source: Authors' own illustration, ENGIE Impact GmbH (2023)

Table 11 shows the specific production costs separated according to the shares for H_2 and NH_3 synthesis. Both shares consider operating costs and TIC. When calculating the specific cost shares for NH_3 synthesis, a depreciation period of 10 years and 8,000 annual operating hours are assumed.

TABLE 11. GREEN AMMONIA SPECIFIC PRODUCTION COSTS

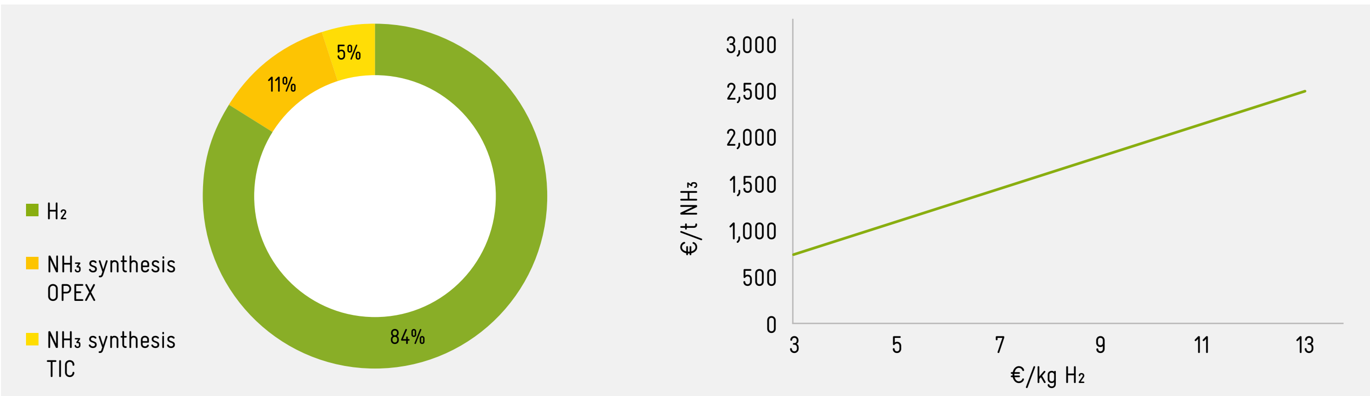
Specific Production Costs

	H_2	**NH_3 synthesis**	**Total**
EUR/t NH_3	1,412	274	1,686
	84%	16%	100%

Source: Authors' own illustration, ENGIE Impact GmbH (2023)

As with the specific energy requirement, the calculation shows that the main cost driver is hydrogen production. At around 84%, this is more than three quarters of the total production costs for ammonia. The 16% NH_3 synthesis cost is divided into 11% operating costs and 5% TIC. The influence of the levelised cost of hydrogen on the NH_3 production is shown in Figure 13.

FIGURE 12. IMPACT OF H_2 PRICE ON THE LCOA



Source: Authors' own illistration, ENGIE Impact GmbH (2023)

2.5.2 Levelised cost of hydrogen

The green hydrogen production potential for solar PV energy in Jordan and the associated levelised cost of hydrogen production were estimated. For this purpose, a high-level geographical analysis has been performed, estimating the regional hydrogen production potential and specific cost based on the local solar potential. A map of the solar PV capacity factor with assumptions can be found in the Appendix in Figure 27 and Table 21.

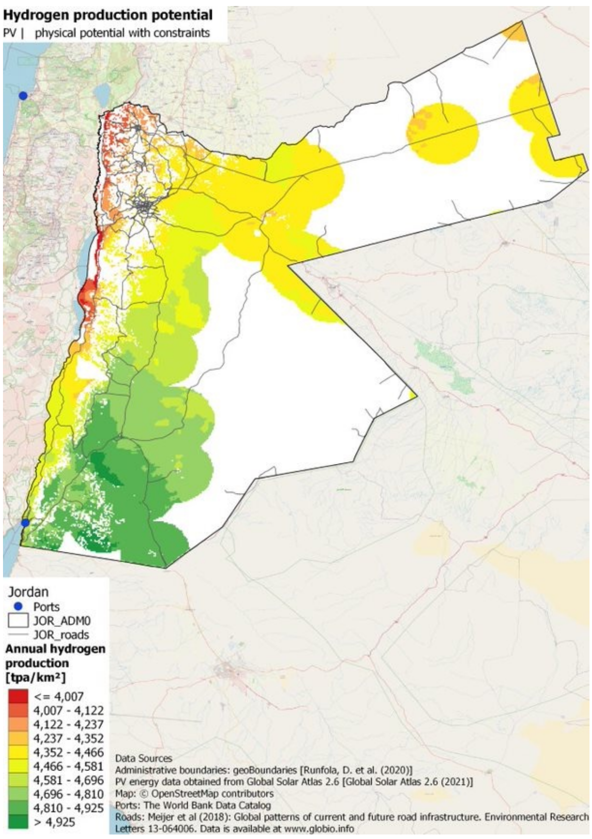
In the geographic information system (GIS) analysis, the technical hydrogen production potential is estimated. The technical production potential describes the maximum annual hydrogen quantity that can be produced in a defined area, considering the local PV energy yield, conversion efficiencies (electrolysis) as well as land-use constraints. Land-use constraints are applied according to the level 2 constraints based on the Energy Sector Management Assistance Program (ESMAP) (ESMAP Global Solar Atlas, 2020), which considers areas with rugged terrain, extreme remoteness, built-up environments, dense forests and, additionally, cropland and conservation areas as exclusion areas for the installation of solar PV plants. Therefore, areas with these land-use constraints are excluded from the analysis and the overall production potential (for electricity and hydrogen) is reduced accordingly.

Due to the land-use constraints applied, in regions with high population densities, complex terrain or large nature reserve areas, locally large areas are considered as unsuitable for the production of hydrogen. The exclusion areas are shown as white space on the following coloured maps. Due to the land-use constraints, several areas were not considered for hydrogen production, including the eastern area of the Ma'an Governorate and large parts of the Mafraq Governorate.

Figure 14 gives an indication of the maximum technical H_2 potential (MTHP) for a specified area, taking into account the land-use restrictions. The specific average H_2 potential for Jordan is 4,571 tpa/km². The specific MTHP for the Ma'an Governorate is 4,761 tpa/km². Other areas with significant specific potential in the southern part of the country are the Aqaba Governorate and the Tafilah Governorate with estimated MTHP of 4,715 tpa/km² and 4,586 tpa/km², respectively. Note that local water constraints are not considered on the hydrogen potential maps and must be assessed on a case-by-case basis.

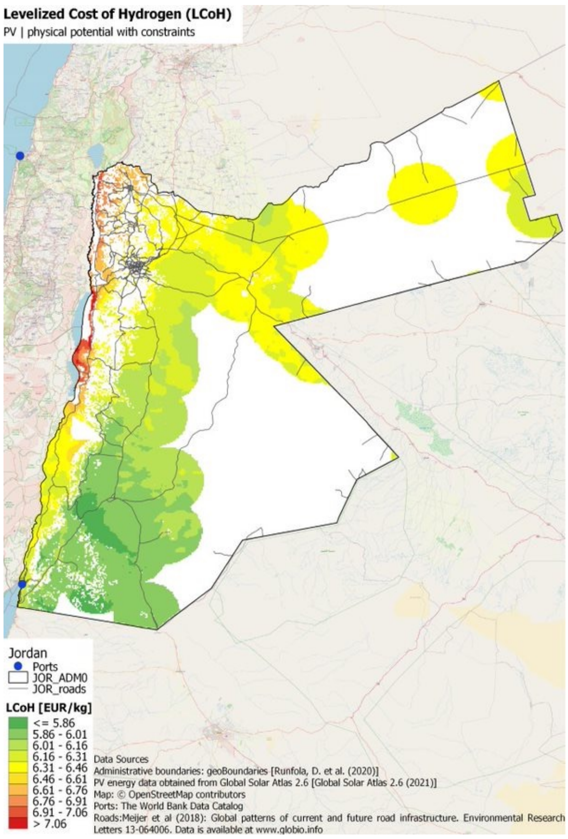
As can be seen on the maps, the areas with the greatest potential are located in the southern parts of the country. The proximity of the southern Aqaba Governorate would be advantageous if a project were to be set up to produce green hydrogen for export. The areas with most land without constraints can be observed in the Zarqa and Aqaba Governorates and as a central vertical strip through the country, crossing the western parts of the Mafraq, Amman, Ma'an, respectively the eastern parts of the Karak and Tafilah, Governorates.

FIGURE 13. HYDROGEN PRODUCTION POTENTIAL IN JORDAN



Source: Authors' own illustration, ENGIE Impact GmbH (2023)

FIGURE 14. LEVELISED COST OF HYDROGEN (LCOH) IN JORDAN



Source: Authors' own illustration, ENGIE Impact GmbH (2023)

Figure 15 shows the spatial distribution of the levelised cost of hydrogen (in EUR/kg) in Jordan taking into account land-use constraints (level 2 constraints). The spatial distribution of the LCoH is directly proportional to the local irradiance and power yield of the PV plants.

The lowest LCoH level of EUR ≤ 5.86/kg can be observed in the western part of the Ma'an and the southeastern part of the Aqaba Governorates, while the highest LCoH level of USD > 7.06/kg can be observed in the coastal regions in the Balqa, and Figure 19 show LCoH without land-use constraints and the H_2 production potential.

The capacity factor for PV, the average specific hydrogen production potential per region, the total hydrogen production potential per region and the calculated average levelised cost of hydrogen per region are shown in the table below. The top 5 locations in terms of renewable energy and hydrogen production potential in Jordan are shown in Table 12; the complete table with all locations can be found in the Appendix.

TABLE 12. SUMMARY OF PV AND GREEN HYDROGEN PRODUCTION POTENTIAL BY REGION

Region	PV capacity factor [%]	Theoretic green hydrogen production potential		LCoH
		Area-specific potential [tpa/km²]	Total potential [tpa]	[EUR/kg]
Ma'an	22.96%	4,761	59,457,763	6
Aqaba	22.66%	4,715	20,827,318	6.08
Tafilah	22.25%	4,586	6,805,013	6.19
Amman	22.02%	4,498	22,905,373	6.25
Karak	21.88%	4,495	10,243,093	6.3

Source: Authors' own illustration, ENGIE Impact GmbH (2023)

3 POTENTIAL GREEN HYDROGEN BUSINESS CASES

3. Potential Green Hydrogen Business Cases

To understand the potential interest of local businesses in Jordan in converting from current conventional hydrogen consumption to producing their own green hydrogen, detailed research was conducted with private sector representatives. The main sources of information were industry interviews with current grey hydrogen users, during which they were asked about their hydrogen processes, motivation for interest in green hydrogen production, perceived challenges in converting to local green hydrogen production, hydrogen (or derivative product) demand and cost levels, land availability for PV and access to sufficient water. A list of topics discussed can be found in the Appendix in Table 21. The attached list is not exhaustive and additional informal discussions, e-mail exchanges and literature reviews were used to gain a full picture of the private sector in Jordan and its willingness to convert to green hydrogen. The chosen method of research allowed the responders of this study the freedom of response that was further supplemented by a detailed industry sector analysis. Based on this information, illustrative business cases were developed which represent typical sector scenarios replacing grey hydrogen used in the manufacturing process with green hydrogen.

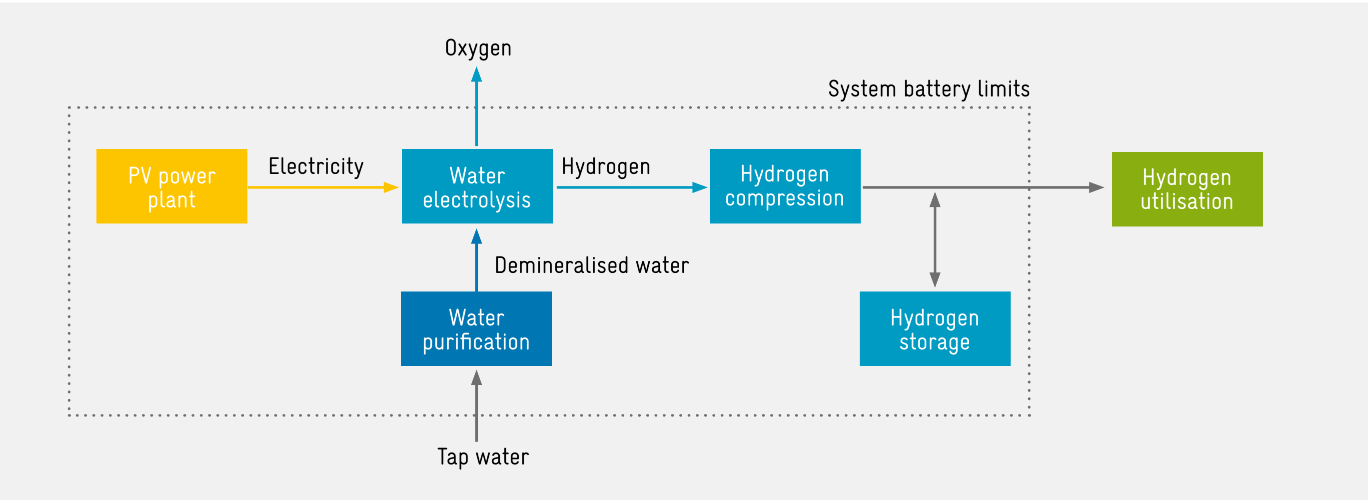
The premise of the business cases is the replacement of current grey hydrogen with locally produced green hydrogen, which would be created solely using carbon-free electricity supplied from on-site solar PV. These business cases focus on current grey hydrogen consumers where the hydrogen, or hydrogen derivative product, is either a production feedstock or an element in the current manufacturing process (e.g. process gas). Use cases for hydrogen as a thermal or energy carrier or as a transportation fuel are not considered within this study. The production concept for the business cases is shown in Figure 26.

For each business case, a high-level cost-benefit analysis was carried out based on estimated sizing and cost of the electrolyser system and solar PV plant, as well as the LCoH as per the local solar resource. To estimate the system cost, the PV and the electrolysis system are sized to meet the H_2 demand, and it is assumed that both are implemented as a combined greenfield project without pre-existing equipment. The methodology for the calculation is described in the Appendix and the key assumptions used are shown in Table 22.

When considering green hydrogen production solely powered by PV electricity, due to the variable nature of the solar resource, the sizing of system components will be influenced by the operational mode of the H_2 used in the end production process. Although the same volume in annual tons of H_2 produced is the same, for business operations where a constant or baseload supply of hydrogen is required, the PV plant must be oversized to ensure minimum baseload production even during non-peak solar resources. In cases where flexible production is possible, i.e. production scheduled following the solar resource, then PV plants could be significantly smaller, but the electrolyser would need to be oversized to fully utilise solar peak production. The choice between flexible and baseline H_2 production also has a significant impact on system costs and the resulting LCoH, particularly in cases where extra electricity from the PV plan can be sold back to the grid, which can account for substantial additional revenue. Please see the Appendix for a thorough explanation.

For each case, the complete LCoH is calculated. In addition, the "effective" LCoH is calculated by adding back the discounted value of electricity sales revenue and oxygen sales revenue, which

FIGURE 15. GREEN HYDROGEN PRODUCTION CONCEPT



Source: Authors' own illustration, ENGIE Impact GmbH (2023), based on (Gulf Energy, 2023) are benefits which would not accrue without the project. Finally, the effective LCoH is also provided for informational purposes, also taking into account the value of avoided GHG emissions.

The LCoH presented in the case studies varies from the global specific LCoH presented on the GIS maps as the GIS maps represent simplified costs of production, which is a common standard methodology, and are comparable to what is found on the LCoH in literature and other studies. The LCoH in the business cases, on the other hand, include additional costs which the company will likely incur, for example, import taxes (when applicable), inflation on operational expenditures (OPEX), capitalised financing costs and increased CAPEX and OPEX related to system sizing (or oversizing) required to achieve the specified H2 production profile as well as additional oversizing of the PV field to ensure a minimum level of annual production taking into account degradation of both the PV and the electrolyser system over time, which requires adding significant additional PV capacity. Together, these result in an LCoH which can, in some cases, vary significantly from the simplified specific production costs.

Given the comparatively low plant utilisation rates, due to the variable solar resource and lack of economies-of-scale production, small-scale local green hydrogen is not currently cost-competitive with conventional sources on a specific cost-of-production basis. However, as electrolyser technology costs come down and the decarbonisation of industry takes on a more important role with financial consequences, for example, through carbon tax, this could change. Therefore, the business cases set out to determine what it would take in terms of financial support to make the local production of green hydrogen, powered by solar PV, cost-effective for local businesses in Jordan.

Note: the business cases are intended for illustrative purposes only and do not represent an actual company.

3.1 Case 1. Green hydrogen to ammonia for fertiliser

A fertiliser production company located near Aqaba, Jordan, which currently imports all raw materials for fertiliser mixing is considering expanding to include local green H_2 production. In the first phase, the ammonia demand would be ~28,333 tpa NH_3. Given that ~18% hydrogen and ~82% nitrogen is required to produce ammonia, for 28,333 tons/year of NH_3 production, 5,000 tpa H_2 is required.

Given the solar resource in the Aqaba region of Jordan, to produce 5,000 tpa of H_2 in baseload operational mode a 320 MW PV plant and a 95 MW electrolyser would be required. In flexible operation mode, the PV plant would only need to be 188 MW and the electrolysis system would need to be sized at 141 MW. As can be seen from Table 13, the overall investment costs for baseload production are 20% higher than for flexible operating mode. About 5,000 tons of oxygen per year would be produced as a by-product of the hydrogen production process, which could be sold to industrial users (assumed price EUR 0.40/kg). The table below shows system sizing for both flexible and baseline operational modes.

TABLE 13. BUSINESS CASE 1. GREEN HYDROGEN FOR AMMONIA FERTILISER PRODUCTION LCOH

System Sizing	Flexible Operation	Baseload Operation
Installed PV power (kWp)	188,911	320,760
Design power electrolysis (kW)	141,818	95,821
Annual net electricity generation PV (kWh/year)	358,048,045	607,943,883
Annual net electricity consumption EL (kWh/year)	268,790,323	268,790,323
Total investment cost (EUR thousand)	308,048	372,433

Source: Authors' own illustration, ENGIE Impact GmbH (2023)

The complete assumptions, sizing, cost breakdown and results are shown in Table 22.

Using the cost assumptions as described in Section 3.5 for AEL technology, the resulting specific LCoH is EUR 10.37/kg in baseload operation and EUR 8.45/kg with flexible operation sizing. However, when considering the equivalent value of the surplus PV electricity which could be sold back to the grid, as well as revenue from oxygen sales, the resulting effective LCoH is EUR 4.71/kg with flexible and EUR 3.73/kg with baseload operation sizing.

The key difference is the volume of extra electricity which could be sold, effectively lowering the effective LCoH by EUR 3.44/kWh. In the baseload case, revenue from the sale of extra electricity and oxygen would cover more than 2/3 of the green H_2 production costs.

Given the target LCoH of EUR 3.09/kg to achieve price parity with conventional H_2 sources, subsidies equalling EUR 1.62/kg or the equivalent of a CAPEX grant of EUR 79 m would be required with flexible operation sizing and EUR 0.64/kg or the equivalent of a EUR 31 m CAPEX grant with baseload operation sizing would be required.

The breakdown of the LCoH for the business case is presented in the following table.

The replacement of conventional H_2 with green H_2 would result in a reduction of 50,000 tons/p.a. of CO_2 emissions, which has a cost of carbon of over EUR 106 m (assuming High-Level Commission on Carbon Prices) over the 25-year lifetime of the plant.

The next step in the process is to convert the green H_2 to NH_3.

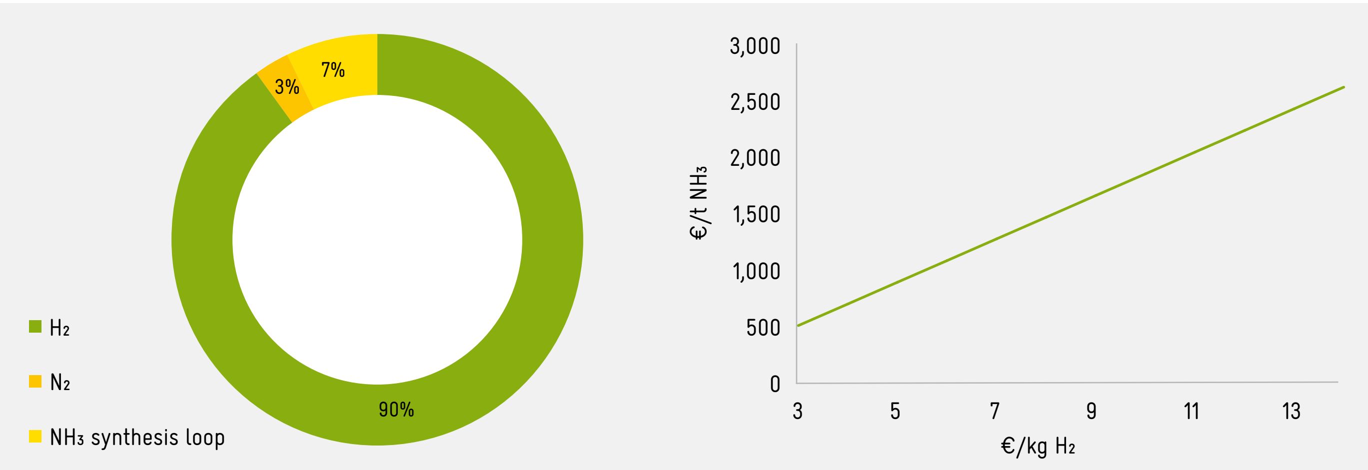
Given the small size of the ammonia plant, the CAPEX is estimated to be EUR ~34.06 m (around EUR 131 /ton annual capacity). Applying the previously calculated LCoH of EUR 10.37/kg H_2 and the local cost of electricity of EUR 0.05/kWh for the ASU, the resulting levelised cost of ammonia (LCoA) would be EUR 1,974/ton and would range from EUR 769-2,710/ton, based on the different effective LCoH presented.

TABLE 14. BUSINESS CASE 1. GREEN HYDROGEN FOR AMMONIA PRODUCTION LCOH BREAKDOWN

Levelised Cost of Hydrogen	Flexible Operation	Baseload Operation
	EUR/kg	EUR/kg
Levelised Cost of Hydrogen	**8.45**	**10.37**
Equivalent levelised value of benefits per kg H_2 produced		
Equivalent value of oxygen revenue per kg H_2 produced	3.20	3.20
Equivalent value of electricity revenue per kg H_2 produced	0.54	3.44
Effective LCoH (incl. electricity and oxygen sales)	4.71	3.73
Effective LCoH (incl. revenue + CO_2 avoided costs)	3.92	2.94
Target LCoH (cost comparable to market price for grey H_2)	3.09	3.09
Required Subsidies		
Effective green H_2 LCoH	4.71	3.73
Target LCoH (cost comparable to market price for grey H_2)	3.09	3.09
Price gap between effective green LCoH and target LCoH [EUR/kg]	1.62	0.64
Subsidy required to achieve target (investment subsidy in EUR)	79,941	31,578

Source: Authors' own illustration, ENGIE Impact GmbH (2023)

FIGURE 16. IMPACT OF THE H_2 PRICE ON THE LCOA



Source: Authors' own illustration, ENGIE Impact GmbH (2023)

3.2 Case 2. Green hydrogen for food production

A food sector company located in Aqaba region of Jordan produces margarine and uses H_2 for the hydrogenation of its products to increase the melting point, as a preservative and to harden the texture. The plant can process 3,000 tons of oil per year and the process is set up to process 5 tons of oil per batch, which requires 6 kg H_2 per ton, with a total 18 tpa of H_2. As it runs a batch process operation and short interruptions in hydrogen flow do not impact the final product, flexible operation of the electrolysers can be followed.

Given the solar resource in the Aqaba region, to produce 18 tpa of H_2 in flexible mode a ~0.68 MW PV plant and a 0.51 MW electrolyser would be required. If the system was sized to run in baseload operational mode, then a 1.16 MW PV system and a 0.35 MW electrolysis system would be required. In this case, the PV system would produce around 1.5x as much electricity annually as needed for H_2 production, which could be sold to the grid, providing a significant source of revenue, or used to offset electricity consumption in other parts of the production facility.

In addition, 144 tons of oxygen per year would be produced as a by-product of the hydrogen production, which could be sold to industrial users (assumed price EUR 0.40/kg). If baseline operation sizing was used, then to ensure consistent minimum production throughout the day the PV plant would need to be oversized at 1.16 MW and the electrolyser system size could be reduced to 0.34 MW. This would result in nearly 40% more electricity production for almost the same initial investment cost and the resulting “extra” electricity could be sold, generating an additional revenue stream or used to offset electricity consumption in other parts of the production facility.

TABLE 15. BUSINESS CASE 2. GREEN HYDROGEN FOR FOOD PRODUCTION SYSTEM SIZING

System Sizing	Flexible Operation	Baseload Operation
Installed PV power (kWp)	680	1,155
Design power electrolysis (kW)	511	345
Annual net electricity generation PV (kWh/year)	1,288,973	2,188,598
Annual net electricity consumption EL (kWh/year)	967,645	967,645
Total investment cost (EUR thousand)	1,680	1,733

Source: Authors’ own illustration, ENGIE Impact GmbH (2023)

Using the cost assumptions as described in Section 3.5 for AEL technology, the resulting specific LCoH is EUR 12.76/kg in baseload operation and EUR 11.91/kg with flexible operation sizing. However, when considering the equivalent value of the surplus PV electricity which could be sold back to the grid, as well as revenue from oxygen sales, the resulting effective LCoH is EUR 8.17/kg with flexible and EUR 6.13/kg with baseload operation sizing. As both methods have nearly the same investment costs and produce the same volume of H_2 annually, the difference is in the value of the sales of the extra electricity, which in the baseload case contributes an equivalent value of EUR 3.44/kg of H_2 produced.

Given the target LCoH of EUR 3.09/kg to achieve price parity with conventional H2 sources, subsidies equalling EUR 5.08/kg or the equivalent of a CAPEX grant of EUR 922 k would be required with flexible operation sizing, and EUR 3.04/kg or the equivalent of a EUR 540 k CAPEX grant with baseload operation sizing would be required.

The breakdown of the LCoH for the business case is presented in the following table. The complete assumptions, sizing, cost breakdown and results are show in Table 20 in the Appendix.

TABLE 16. BUSINESS CASE 2. GREEN HYDROGEN FOR FOOD PRODUCTION LCOH BREAKDOWN

Levelised Cost of Hydrogen	Flexible Operation	Baseload Operation
	EUR/kg	EUR/kg
Levelised Cost of Hydrogen	**11.91**	**12.76**
Equivalent levelised value of benefits per kg H_2 produced		
Equivalent value of oxygen revenue per kg H_2 produced	3.20	3.20
Equivalent value of electricity revenue per kg H_2 produced	0.54	3.44
Effective LCoH (incl. electricity and oxygen sales)	8.17	6.13
Effective LCoH (inc. revenue + CO_2 avoided costs)	7.38	5.34
Target LCoH (cost comparable to market price for grey H_2)	3.09	3.09
Required Subsidies		
Effective green H_2 LCoH	8.17	6.13
Target LCoH (cost comparable to market price for grey H_2)	3.09	3.09
Price gap between effective green LCoH and target LCoH [EUR/kg]	5.08	3.04
Subsidy required to achieve target (investment subsidy in EUR)	922	540

Source: Authors’ own illustration, ENGIE Impact GmbH (2023)

The replacement of conventional H_2 with green H_2 would result in a reduction of 180 tpa CO_2 emissions, which has a cost of carbon of over EUR 390,000 (assuming High-Level Commission on Carbon Prices (HLCCP)) central scenario prices over the 25-year lifetime of the plant.

3.3 Business case conclusions

As can be seen in the illustrative business cases, the production of green hydrogen solely by means of solar energy will require significant financial incentives over the short, medium and long term to become cost-competitive with conventional H_2 sources. This is due to the required system "oversizing" needed to enable the constant production of H_2, as well as a lack of economies of scale due to the small production sizes compared to large centralised production. Alternative sources of green energy could be harnessed to reduce the required system size and increase plant utilisation enabling 24/7 production, thus significantly lowering the overall LCoH.

The business cases further demonstrate the significant impact of system sizing on the overall financial feasibility due to operational method, tapping into additional revenue streams and the financial support structure. Although oversizing the PV system increases the overall initial investment cost, in most cases the resulting revenue from the sale of "extra" green energy more than offsets this cost and serves to subsidise the cost of H_2 production. Furthermore, financial incentives such as grants for the PV or electrolyser system could help to enable the small-scale decentralised production of green H_2 to become financially viable in the medium term.

4 THE WAY FORWARD

4. The way forward

4.1 Challenges and considerations for hydrogen implementation

Considerations for the implementation renewable energy and electrolysis facilities for hydrogen production at existing industrial facilities include:

- **Investment costs.** High investment costs leading to production costs that are higher than market costs and a lack of sufficient accessible financing.
- **Regulatory framework and approval process.** As decentralised production of green hydrogen is relatively new, the regulatory, environmental requirements and permitting regulations are non-existent or unclear. This adds significant uncertainty and additional time and overheads to the project development process.
- **Operation staff.** Trained staff available for operations & maintenance activities.
- **Supply chain shortages.** In recent years there have been a number of factors (COVID, Ukraine, etc.) impacting supply chain components, parts and materials leading to long lead times for delivery of equipment.
- **Area requirements.** Availability of sufficient space for installation of an electrolysis plant, hydrogen storage and balance-of-plant equipment as well as the PV plant. The average space requirement for 1 MWp solar PV generating capacity requires at least 5 acres (Land Use & Solar Development, 2023).
- **Logistical issues.** Potential issues in carrying out construction while the existing operations continue, as well as potential impacts on production and what types of tie-ins are necessary.
- **Design and engineering of plant.** Hydrogen is highly flammable and requires strict safety protocols to ensure safe handling and storage. Special attention should be given to the location of storage equipment, separation distances, potential for dominos effects, integrated design safety functions.
- **Power supply.** Is a reliable power supply as well as back-up power supply secured? There will be increased metering requirements to demonstrate the use of green electricity for green H_2 production.

- **Water supply.** Availability of water in the required quality and quantity (tap water or demineralised water). Hydrogen production requires significant quantities of water. It is crucial to build a green hydrogen industry in such a way that it will not negatively affect water security. Water desalination is one of the proposed solutions that can reduce the impact of the hydrogen water footprint.
- **Safety aspects.** Integration of hydrogen production and the storage facility into the existing safety concept of the existing industrial plant site.
- **Control and operation.** Integration of hydrogen production and the storage facility into existing control systems.
- **Supply considerations.** Is a constant hydrogen supply necessary for operations and is this possible given local renewable resources?
- **Storage facilities.** Adequate hydrogen and electricity storage facilities are required if production relies on VRE to ensure uninterrupted production.

4.2 Opportunities and supporting frameworks for hydrogen implementation

The production of green hydrogen offers numerous opportunities which are in line with the country's climate and decarbonisation policies and their targets, including:

- The Master Strategy for the Energy Sector 2020–2030, developed by the Ministry of Energy and Mineral Resources (MEMR), includes provisions for a sustainable future energy supply, diversification of the national energy mix, increased dependency on the share of domestic energy resources, enhanced energy security and reduced energy dependence and cost of electricity supply. The strategy targets a 31% share for renewables of the total power generation capacity and 14% of the total energy mix by 2030.

- The Renewable Energy and Energy Efficiency Law adopted in 2012 to incentivise private sector investment in renewable energy. This addresses different aspects of renewable energy development, including conditions and procedures for developing, connecting and remunerating projects of different scales and applications.

- National Climate Change Policy 2022–2050. Jordan‘s National Climate Change Policy outlines the country‘s commitment to reducing greenhouse gas emissions and adapting to the impacts of climate change while also addressing the country‘s development needs and social priorities. The policy aims to increase Jordan‘s share of renewable energy in the electricity mix to 31% by 2030 and 50% by 2050. This will involve expanding the use of solar and wind power, as well as promoting energy efficiency and conservation.

The development of the green hydrogen sector will:

- Reduce GHG emissions and support the country's clean energy transmission policies, through the decarbonisation of hard-to-abate industrial sectors.

- Decarbonise the agricultural sector through more sustainable production of fertilisers using green ammonia.

- Reduce the country's dependency on hydrogen derivative imports such as ammonia and methanol, and could be a starting point for developing local production capacities for industry.

- Accelerate investment and speed up the country's technological development. In addition, new skilled jobs will be created providing new opportunities to its population.

4.3 Local Jordanian financing instruments

Jordan does not yet have green hydrogen sector-specific financial and policy incentives or preferential mechanisms. The Jordanian government is expected to encourage project developers, green hydrogen producers and public-private partnerships with local and international partners to implement strategically important pilot hydrogen demonstration projects. In the hydrogen market's current technology demonstration phase, public financing, subsidies and fiscal incentive instruments as well as project-specific offtake arrangements are being used globally to reduce the project's financial risks, allowing producers to demonstrate successful operation (and business cases) of green hydrogen in the absence of market mechanisms, policy and financing support frameworks. Jordan's existing Renewable Energy and Energy Efficiency Fund (JREEEF) (Jordan Renewable Energy and Energy Efficiency Fund, 2020) can be instrumental if it is also given the mandate to promote and develop green hydrogen projects together with private sectors. However, as a starting point to encourage more investments in green hydrogen sector, a national-level green hydrogen strategy needs to be established for Jordan. The energy, industry and transport sector policies, in particular, need to consider green hydrogen as another clean technology and align their sectoral low-carbon roadmaps with green hydrogen-specific actions.

4.4 Green hydrogen financing opportunities for German companies

There are four categories of financing opportunities for German companies active in green hydrogen technologies:

EU-level funding opportunities
The Clean Hydrogen Partnership (public-private partnership) aims to provide research and innovation funding for hydrogen projects for European companies (Hydrogen Europe, 2023). The funding comes in the form of grants and European Union (EU) co-funding for green hydrogen production, storage, distribution, transportation, heat and power application, hydrogen valley development, etc.

Another example is the ETS Innovation Fund (European Union, 2023) for H_2 demonstration projects, where money raised via the EU ETS (European Union Emissions Trading System) is reinvested into the Innovation Fund (public-private partnership). Under grant agreements, the fund can be used for the demonstration of innovative low-carbon technologies including green hydrogen. For example, one of the hydrogen projects that received funding from the ETS Innovation Fund is the fossil-free steel production "HYBRIT" project in Sweden.

National public funding for hydrogen projects specific to the EU Member State
Examples of national public funding include the German H2 Global mechanism (H2 Global Stiftung, 2022). H2 Global is an auction-based financing mechanism for green hydrogen which will conclude long-term purchase contracts on the supply side and short-term resale contracts on the demand side, ensuring planning and investment security for green H_2 investments, given the current lack of fully functioning green H_2 markets. The concept provides for the compensation of the difference between the purchase price (production plus transport costs) and the sales price (currently the market price for fossil hydrogen) for green H_2 and H_2-based derivatives. The first tender was launched in November 2022 as an auction for green ammonia, e-methanol and sustainable aviation fuel from international producers (outside EU and EFTA countries). The concept is developed with funding from the German Federal Ministry for Economic Affairs and Climate Action.

In addition, in 2022 the Federal Government launched the "Hydrogen Pilot Office" website, which provides combined information for hydrogen funding opportunities at national, EU and international level. The International Hydrogen Ramp-up Programme (H2Uppp) supports German small and medium-sized enterprises (SMEs) in identifying, preparing and implementing pilot projects for the production and use of green hydrogen in developing and emerging countries (BMWK, 2023). Guidance on sources of funding can be found on the BMWK website "Funding advice – Hydrogen Guidance Service" One-Stop-Shop – Wasserstoff – Funding advice (bmwk.de).

National and European banks
European and national banks such as the European Investment Bank (EIB) and Kreditanstalt für Wiederaufbau (KFW) leverage private capital investments in green hydrogen projects. A wide variety of financing instruments including debt and equity finance, as well as investment guarantees, are available in addition to the previously mentioned EU support programmes.

For instance, the EIB will provide financing advisory support as well as dedicated EIB financing products (European Investment Bank, 2021) for green hydrogen projects introduced through Hydrogen Europe – the association representing European industry, research and national and regional associations in the hydrogen and fuel cell sectors.

Private finance such as venture capital funds
Private finance such as venture capital funds (e.g. Breakthrough Energy founded by Bill Gates) and private banks are also showing interests in investing in the hydrogen sector. With over $1 billion raised in committed capital, Breakthrough Energy, through its Energy Catalyst platform, funds and invests in project companies utilising emerging climate technologies including clean hydrogen, storage, sustainable aviation fuel, etc. (Breakthrough Energy, 2022). A special programme in Europe has recently been established (Breakthrough Energy Europe) to support research and innovation in clean technology, including green hydrogen (Breakthrough Energy, 2022).

However, hydrogen projects solely based on private financing have yet to gain momentum given that there is not yet fully functioning markets for off-takers or pricing of green hydrogen products.

4.5 Where to go for more information

The following resources are available to learn more about investing in (H_2) in Jordan:

Jordan Investment Commission (JIC) is the governmental agency responsible for promoting and facilitating investment in Jordan. It can provide information on investment opportunities in green hydrogen, as well as regulatory frameworks and investment incentives.

Jordan Renewable Energy and Energy Efficiency Fund (JREEEF) is a government entity that provides financing and support for renewable energy and energy efficiency projects in Jordan. The Fund provides programmes that support the development of green hydrogen projects.

Jordanian Ministry of Energy and Mineral Resources (MEMR) is the government ministry responsible for energy and mineral resources in Jordan. It is also involved in promoting and supporting the development of renewable energy, including green hydrogen.

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Appendix

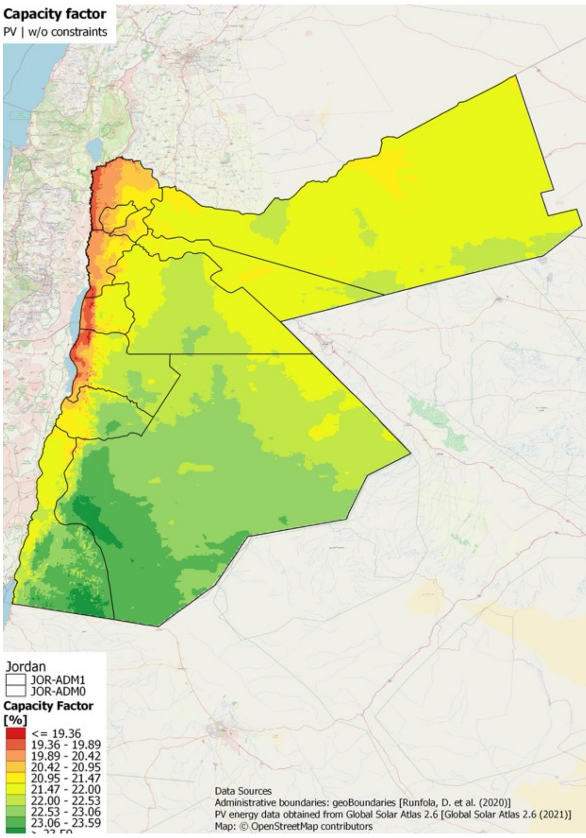
TABLE 17. JORDAN ELECTRICITY TARIFF

Residential (Subsidized)	**fils/kWh**	**EUR/kWh**
From 1-300 kwh/month	50	0.070
From 301-600 kwh/month	100	0.141
More than 600 kwh/month	200	0.282
Residential (Not subsidised)		
From 1-1,000 kwh/month	120	0.169
More than 1,000 kwh/month	150	0.211
Commercial		
From 1-2,000 kwh/month	120	0.169
More than 2,000 kwh/month	152	0.214
Small Industries		
From 1-10,000 kwh/month	60	0.084
More than 10,000 kwh/month	68	0.096
Medium Industries		
Day supply	68	0.096
Night supply	65	0.091
Big Industries		
Day supply	124	0.175
Night supply	109	0.153
Electric Car Charging Meter for Residential		
From 1-1,000 kwh/month	112	0.158
More than 1,000 kwh/month	200	0.282
Agricultural		
Day supply	55	0.077
Night supply	49	0.069
Hotels		
Day supply	82	0.115
Night supply	82	0.115
Minimum Monthly Consumption Cut-Off		
Ordinary Consumers	1.75	0.002
Other Consumers	2	0.003
Radio & Television Tariff	152	0.214
Banking Sector Tariff	285	0.401
Water Pumping Station	105	0.148
Street Lighting	114	0.160
Jordanian Armed Forces	146	0.206
Private Hospitals	140	0.197
Ports Corporation	159	0.224
Mixed (Agricultural/Commercial)	100	0.141

Source: Authors' own illustration, ENGIE Impact GmbH (2023) based on (Energy and Minerals Regulatory Commission, 2023)

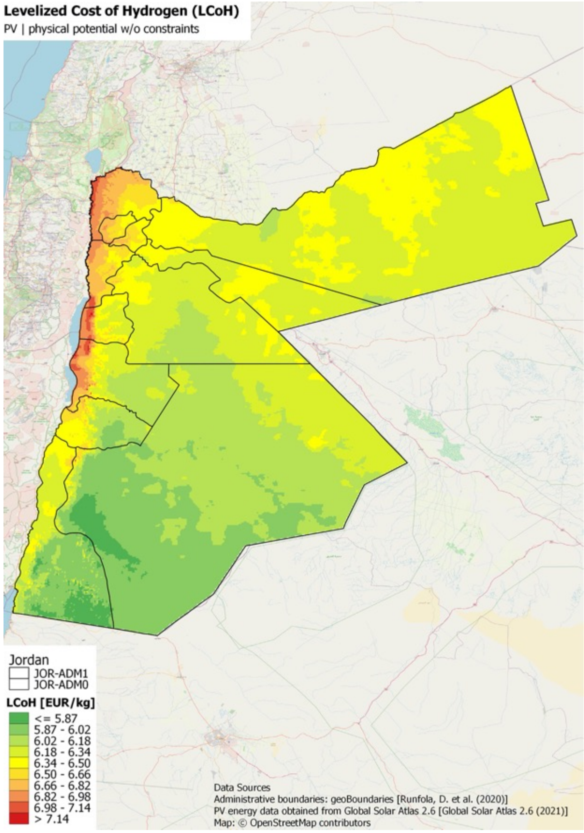
LCoH GIS maps and cost assumptions

FIGURE 17. SOLAR CAPACITY FACTOR IN JORDAN



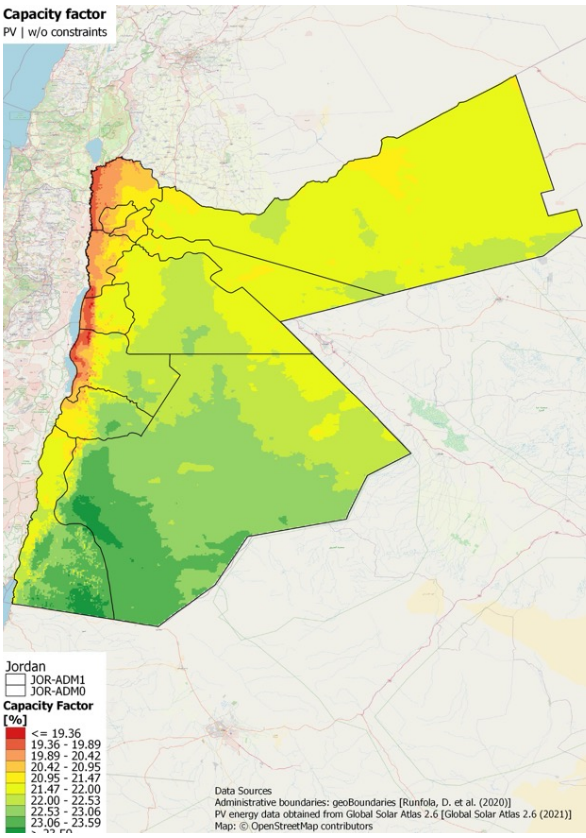
Source: Authors' own illustration, ENGIE Impact GmbH (2023)

FIGURE 18. LEVELISED COST OF HYDROGEN (LCOH)



Source: Authors' own illustration, ENGIE Impact GmbH, 2023

FIGURE 19. HYDROGEN PRODUCTION POTENTIAL



Source: Authors' own illustration, ENGIE Impact GmbH, 2023

TABLE 18. GIS MAP LCOH ASSUMPTIONS

Levelised Cost of Hydrogen Assumptions (GIS maps)		
Water price	4	EUR/m3
Electrolysis efficiency	62	%
CAPEX PV	713	EUR/kWi
CAPEX Electrolysis	1,300	EUR/kW
fixOPEX PV	20	EUR/kW/a
fixOPEX Electrolysis	15	EUR/kW/a
varOPEX PV	0	EUR/kWh/a
varOPEX Electrolysis	0	EUR/kg/a

Source: Authors' own illustration, ENGIE Impact GmbH (2023)

TABLE 19. SUMMARY OF PV AND GREEN HYDROGEN PRODUCTION POTENTIAL BY REGION

Region	PV capacity factor PV [%]	Theoretic green hydrogen production potential		LCoH
		Area-specific potential [tpa/km²]	Total potential [tpa]	[EUR/kg]
Ma'an	22.96%	4,761	59,457,763	6
Aqaba	22.66%	4,715	20,827,318	6.08
Tafilah	22.25%	4,586	6,805,013	6.19
Amman	22.02%	4,498	22,905,373	6.25
Karak	21.88%	4,495	10,243,093	6.3
Mafraq	21.75%	4,406	38,921,529	6.32
Zarqa	21.73%	4,428	13,473,744	6.33
Madaba	21.23%	4,337	1,361,764	6.49
Jarash	21.06%	4,273	367,437	6.53
Ajlun	20.68%	4,194	364,864	6.65
Irbid	20.53%	4,152	2,777,449	6.7
Balqa	20.51%	4,176	1,849,828	6.7

Source: Authors' own illustration, ENGIE Impact GmbH (2023)

Potential business case questionnaire

TABLE 20. CASE STUDIES QUESTIONNAIRE

Question	
1	Does the Company have decarbonisation goals/objectives? Are these major factors in your current investment planning?
2	Current use of hydrogen/ammonia (processes used, volume, source)
3	How do you currently transport/store your hydrogen?
4	Have you installed, or do you plan to install, PV at your facility? If not, why not?
5	Do you face challenges in the supply chain (reliable grid electricity, sourcing feedstock since COVID and Ukraine, etc.)?
6	Have you considered local green H_2 production? What aspects are you in favour of? What against?
7	Opportunities for improvement. What regulatory/policy changes would make it easier for you to do business? What types of incentives or financial support for modernisation/decarbonisation do you wish were available?

Source: Authors' own illustration, ENGIE Impact GmbH (2023)

Baseload vs flexible operation explanation

It is necessary to keep in mind that oversizing of both PV and EL for a baseload H_2 supply is always required when operating hydrogen production from PV. For example:

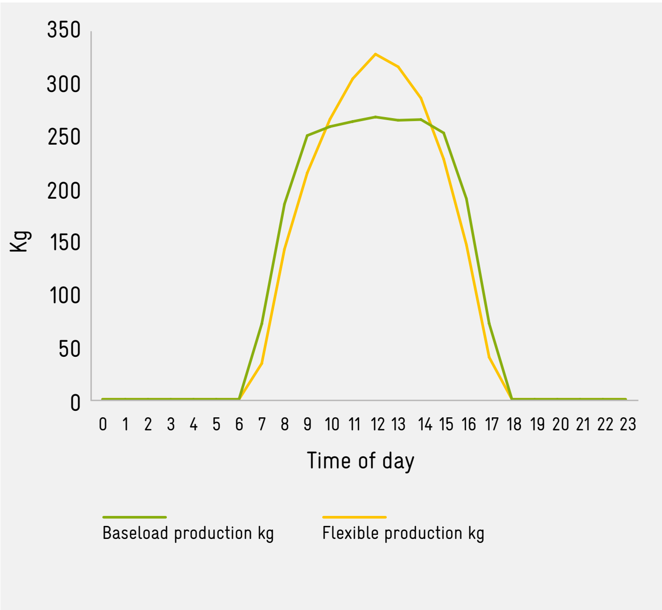
- Consider a H_2 demand of 800 tpa, with a baseload hourly demand of pprox.. 91 kg/h.
- This requires, at minimum, an electrolyser of approx. 5 MW if it the electrolyser would be running 24/7/365 at full load.
- Considering an average capacity factor of PV systems of 20%, a PV system of 5x the electrolyser capacity is required, at minimum, to supply enough electricity over the course of the year (without matching hourly demand).
- Considering the day/night characteristics of sun light and no electricity storage, the electrolyser needs to be oversized by a factor of approx. 2 (charging H_2 storage during the day).
- In this example, the electrolyser capacity would be at least ~10 MW and the PV capacity would be at least 25 MW.

Since, from an optimisation point of view, the installation of a PV system is less expensive than the installation of an electrolysis system, the PV system is more strongly oversized than the electrolyser.

The following two figures show the same annual volume of H_2 production, in flexible and baseload mode.

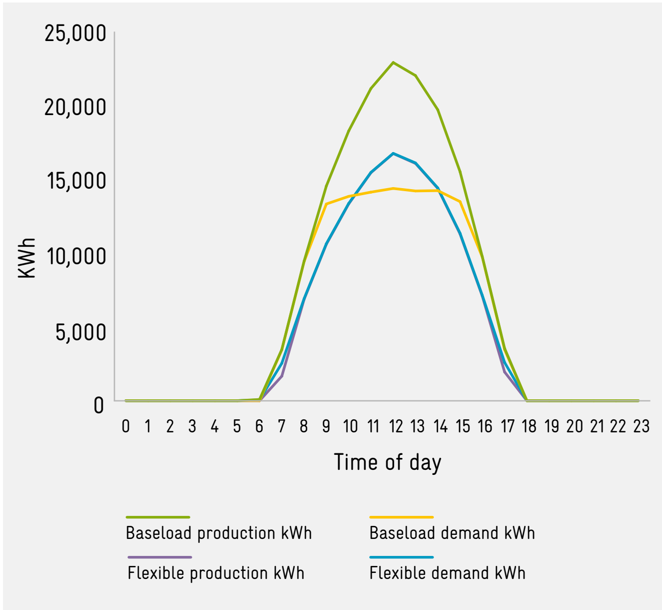
The first figure shows the production of H_2 in flexible mode. In this case, the electrolyser needs to be oversized to be able to take full advantage of the solar peak. Whereas the green line shows production under baseload where more H_2 is produced during off-peak times, filling the H_2 storage for use when needed. However, in order to be able to produce this extra H_2 outside of the solar peak, the PV plant must be scaled up to provide the power. This can be seen in the second figure where the green and yellow lines show the electrical demand of the electrolysers in baseload and the energy production of the PV field. To provide the extra energy during off-peak, the solar field must be oversized. This also results in significant "extra" electricity (the difference between the green and yellow lines) during peak solar production.

FIGURE 20. FLEXIBLE VS BASELOAD H_2 PRODUCTION



Source: Authors' own illustration, ENGIE Impact GmbH (2023)

FIGURE 21. FLEXIBLE VS BASELOAD ELECTRICITY PRODUCTION AND CONSUMPTION



Source: Authors' own illustration, ENGIE Impact GmbH (2023)

Business case financial calculation methodology

The business cases presented are illustrative of the conversion to green hydrogen for current conventional hydrogen consumers. As the business cases focus on the grey-to-green H_2 conversion, the indicative financial assessment is based on the levelised cost of hydrogen (LCoH) and the "effective" LCoH. The LCoH represents the cost to produce 1 unit (1 kg) of hydrogen, taking into account the time value of money in the form of the applied discount rate. It is calculated by dividing the total discounted lifetime system costs by the lifetime discounted volume of hydrogen production.

The first step in calculating the LCoH for the selected business is the choice of investment location, electrolyser technology and required hydrogen production volumes. The CAPEX and OPEX assumptions for the different electrolyser technologies are described in Section 3.5. One of the key aspects of the model is the choice of electrolyser operating mode: baseload or flexible operation mode. Most key calculation assumptions for the business cases are in Table 20.

TABLE 21. JORDAN LCOH BUSINESS CASE ASSUMPTIONS

Business Case Assumptions		
Prices		
Tap water price	EUR/m³	1.88
Electricity tariff (sell)	EUR/kWh	0.05
Oxygen tariff (sell)	EUR/kg	0.40
Taxes		
Import tax rate on PV	%	-
Import tax rate on electrolyser system	%	0.10
Operation		
Oxygen production volume per 1 kg of H_2	kg	8.0
Annual inflation rate (Local)	%	1.3
Water tariff escalation rate	%	2.0
Electricity tariff escalation rate	%	2.0
Oxygen escalation rate	%	0.0
Hydrogen storage	hrs	72
Financing		
Depreciation method		Straight-line depreciation
Operation period	years	25
Discount rate	%	8.0
Debt/equity ratio	%	60.0
Repayment period	years	10
Up-front fee	% of debt capital	1.0
Commitment fee	% of undrawn debt	1.5
Applied interest rate	%	9.0

Source: Authors' own illustration, ENGIE Impact GmbH (2023)

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