Funded by the European Union

MED•GEM MEDITERRANEAN GREEN ELECTRONS AND MOLECULES NETWORK

MINISTRY OF ENERGY AND MINERAL RESOURCES

DECEMBER 31, 2024

Note: This report contains redacted or anonymized data due to confidentiality. Specific details are available upon request, subject to authorization.

ASSESSMENT OF GREEN HYDROGEN FOR INDUSTRIAL HEAT IN JORDAN

2024

OSAMA AYADI

giz International Services

Disclaimer

This report was conducted by Dr. Osama Ayadi following a request from the Ministry of Energy and Mineral Resources (MEMR) under a contract facilitated by MED-GEM Network, funded by the European Union and implemented by GIZ International Services. The analysis, findings, and conclusions expressed in this report are those of the authors and do not necessarily reflect the policies or views of the EU, the GIZ, the MED-GEM Network, the Ministry or any of their affiliates.

The content of this report, including all data, analyses, and recommendations, is the intellectual property of the contracting authority, the MED-GEM Network. The use of the report's content is subject to the terms outlined in this disclaimer. Any reproduction, distribution, or use of the report for any purposes must be authorized by the MED-GEM Network, with the prior notification of MEMR.

The aforementioned parties shall not be held liable for any decisions made based on the data or conclusions presented in this study. While the study represents the best available data and analysis, there is no guarantee regarding its accuracy or completeness. These findings and recommendations should be considered as guidelines rather than as definitive solutions. Sensitive or confidential information in the study has been handled according to the relevant guidelines.

The authors of this study declare that there are no conflicts of interest that could have influenced the analysis or conclusions presented. The report was conducted independently, and no personal, professional, or financial relationships exist that would compromise the integrity of the analyses and findings.

Foreword

Jordan's industrial sector accounts for 25% of GDP, employs 21% of the workforce, and generates $9 billion in exports annually. It produces about 16% of national emissions (5,298 GgCO_2 eq), mainly from fossil fuel use for industrial process heat. Green hydrogen integration is being explored to reduce emissions [1], improve energy security, and support sustainable growth.

With a global commitment to climate action, there are various decarbonization strategies, with new policy incentives and investments in research and development (R&D) for green energy solutions. Among these solutions, green hydrogen is gaining traction and could play a key role in decarbonizing industrial process heat in Jordan. Many industries such as steel manufacturing, chemical production, and cement production, require high temperatures. Green hydrogen, a combustible fuel, is produced through electrolysis powered by renewable energy, making it a green and viable option for replacing the fossil fuels currently in use [2].

Green hydrogen also offers an alternative way to store energy and help balance intermittent electricity production from renewable sources like wind and solar. Hydrogen fuel cells are already being piloted in the transportation sector and are expected to be significant in future aviation fuels. The global momentum for green hydrogen is growing, and it has been recognized as a priority at international climate conferences, emphasizing the need for investment in green hydrogen projects and supportive policies to drive down costs [3].

To use green hydrogen, Jordan will need to develop infrastructure fit for its needs. The focus will be on creating pathways for introducing and scaling green hydrogen use while addressing the technological, financial, and policy barriers [4].

This report is part of The Mediterranean Green Electrons and Molecules Network (MED-GEM) Project, funded by the European Union. MED-GEM is designed to facilitate the energy transition in ‘Southern Neighborhood’ countries. The network's primary aim is to accelerate the deployment of renewable power generation technologies while developing comprehensive policies for the production and trade of renewable hydrogen and its derivatives. Through coordinated engagement with regional stakeholders, MED-GEM plays a critical role in catalyzing policy development, infrastructure planning, industrial partnerships, and financial frameworks.

In this context, MED-GEM Network provides technical assistance to the Ministry of Energy & Mineral Resources to develop a "Preliminary Road Map for Green Hydrogen Usage in the Industry Sector for Heat Application in Jordan". This roadmap represents an important step toward implementing practical applications of green hydrogen technology in Jordan.

This study aims to explore the potential of hydrogen in decarbonizing industrial heat in Jordan [5]. While there are numerous other applications for hydrogen within the energy transition [6], this report will primarily focus on green hydrogen produced from renewable sources for industrial thermal applications.

Key questions addressed in this report include:

- What is the technical and economic potential for introducing and scaling the use of green hydrogen for industrial process heat in Jordan?
- What are the major barriers—technological, financial, and policy—in the emerging hydrogen market in Jordan?
- What pathways exist for introducing and scaling green hydrogen for industry?

The findings from this analysis will be beneficial for large corporate energy buyers and other stakeholders in the market and policy environment. As Jordan moves forward, it is essential to consider the following takeaways:

- The government’s commitment to reducing emissions may require substantial investment in green hydrogen infrastructure.
- Green hydrogen is poised to be a key element in the decarbonization strategy for sectors such as chemicals and cement, and early adopters in these industries should leverage existing policies to facilitate their transition.

Efforts to integrate green hydrogen into Jordan's industrial landscape can be vital in achieving a sustainable energy transition and meeting the country's climate objectives.

[1] IEA - https://prod.iea.org/countries/jordan/emissions
[2] Deloitte - https://www2.deloitte.com/content/dam/Deloitte/us/Documents/Advisory/us-advisory-assessment-of-green-hydrogen-for-industrial-heat.pdf
[3] UNFCC - https://unfccc.int/sites/default/files/NDC/2022-06/UPDATED SUBMISSION OF JORDANS.pdf
[4] GIZ - https://www.giz.de/en/downloads/EE potential in industry JOR.pdf
[5] UNDP - https://www.undp.org/sites/g/files/zskgke326/files/2023-03/National Climate Change Policy of the Hashemite Kingdom of Jordan 2022-2050.pdf
[6] GIZ - https://www.giz.de/en/downloads/giz2023-en-h2pep-sector-analysis-jordan.pdf

Contents

List of Figures

List of Tables

List of Acronyms

AC	Alternating Current
AEM	Anion Exchange Membrane
APC	Arab Potash Company
CAPEX	Capital Expenditure
CFF	Construction Financing Factor
CRF	Capital Recovery Factor
DC	Direct Current
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
EMRC	Energy and Minerals Regulatory Commission
ERC	Electricity Regulatory Commission
FCR	Fixed Charge Rate
GDP	Gross Domestic Product
GHI	Global Horizontal Irradiance
HHV	Higher Heating Value
ICE	Investment Cost of Electrolyzer
JBC	Jordan Bromine Company
JMPC	Jordan Phosphate Mines Company
JNRC	Jordan Nuclear Regulatory Commission
JOD	Jordanian Dinar

JREEEF	Jordan Renewable Energy and Energy Efficiency Fund
KPI	Key Performance Indicator
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Hydrogen
MEMR	Ministry of Energy and Mineral Resources
MIJ	Main/Major Industries in Jordan (JMPC, APC, JBC)
MOU	Memorandum of Understanding
NDC	Nationally Determined Contribution
nEL	Normalizing Efficiency Loss
NRA	Natural Resources Authority
NREL	National Renewable Energy Laboratory
OPEX	Operational Expenditure
PEM	Proton Exchange Membrane
PFF	Project Financing Facility
PPA	Power Purchase Agreement
PtX	Power-to-X
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
R&D	Research and Development
RE	Renewable Energy
SAM	System Advisor Model
SOEC	Solid Oxide Electrolyzer Cell
TBD	To Be Determined
TMY	Typical Meteorological Year
TSM-DEG21C	Thin-film Solar Module - Degradation 21°C
USD	United States Dollar
VOC	Variable Operating Cost

List of Units and Symbols

°C	**Degrees Celsius**
°E	Degrees East
°N	Degrees North

A	Ampere
bar	Bar (Pressure Unit)
Ce	Cerium
Co	Cobalt
Gd	Gadolinium
Imp	Current at Maximum Power Point
Ir	Iridium
Isc	Short Circuit Current
kg	Kilogram
ktoe	Kilo tons of oil equivalent
kW	Kilowatt
kWh	Kilowatt Hour
La	Lanthanum
liters	Liters
m	Meter
m2	Square Meter
Mtpa	Million Tons Per Annum
MWac	Megawatt Alternating Current
MWp	Megawatt Peak
Nm3	Normal Cubic Meter
Pmp	Maximum Power Point
Pt	Platinum
Ru	Ruthenium
tons	Metric Tons (1000 kg)
V	Volt
Vmp	Voltage at Maximum Power Point
Voc	Open Circuit Voltage
W	Watt
Y	Yttrium
Zr	Zirconium
ηEL	Electrolyzer Efficiency

Executive Summary

While Jordan is poised to become a regional hub for exporting green hydrogen, this report explores the significant local potential for green hydrogen utilization. It complements a previous analysis of chemical feedstock applications and anticipates future studies in other sectors, such as transportation. By aligning with Jordan's renewable energy and emissions strategies, focusing on domestic applications like industrial heat decarbonization can deliver immediate local economic and environmental benefits while setting the stage for broader international ambitions in the hydrogen market.

Jordan hosts a diverse range of manufacturing and mining industries, officially categorized into 10 key sectors. The industrial sector consumes approximately 1048.3 ktoe representing 16% of the total energy consumption in the country, and currently emits 5,298 $GgCO_2$ equivalent annually, accounting for 16% of Jordan's total greenhouse gas emissions. Currently, the industry’s energy requirements are met by electricity, natural gas, HFO, diesel, coal and LPG at 408, 230.8, 160.7, 124.9, 110.9, and 13 ktoe respectively.

Decarbonization for industrial heating could be achieved through a set of solutions primarily: energy efficiency practices, solar thermal and electrification of processes. These solutions become increasingly inefficient for high-temperature heat processes limiting the viability of decarbonization in said industries. Green hydrogen, produced through renewable energy-powered electrolysis, represents a potential pathway for industrial decarbonization in these high-thermal demand processes. To evaluate the thermal demand in industrial processes this study conducted surveys, interviews, and site visits, complemented by the analysis of 114 energy audit reports. Through this comprehensive and systematic review this study finds the majority share of energy is spent on heating processes which account for about 61% of the total energy demand of the industry, with the remaining 39% being electricity.

The study also determined the processes requiring high-temperatures (>500 °C) to be 65% of total thermal demand, the key sectors being mining, and construction (cement and steel) accounting for 91%, and 9% respectively. Converted to hydrogen equivalency this sets the maximum demand to be 145 ktons H_2 annually.

This study contains techno-economic analyses that explore various deployment scenarios, examining electrolyzer capacities ranging from 1MW to 100MW. The modeling demonstrates significant economies of scale, with larger installations achieving notably lower production costs. For example, a 1MW electrolyzer installation with an optimal 2.5MW PV sizing presents different economics compared to larger 10MW and 100MW scenarios. The analysis considers various electricity pricing frameworks, including net-metering, medium industry, and large industry tariffs (ranging from 0.059 to 0.094 JOD/kWh, equivalent to approximately 0.083 to 0.133 USD/kWh), comparing these against current fossil fuel costs (0.027-0.065 JOD/kWh, equivalent to approximately 0.038 to 0.092 USD/kWh) for various fuels, including natural gas, HFO, LPG bulk, and diesel. Cost remains a challenge in need of policy-based interventions to overcome.

The Ministry of Energy and Mineral Resources (MEMR)is leading efforts to integrate green hydrogen into Jordan's energy strategy. Already MOUs have been signed alongside the private sector to develop Jordan’s hydrogen production capacity centered on the Aqaba region, leveraging its Red Sea access and planned desalination facilities.

The report identifies a ‘Win-Win-Win’ model/scenario as the recommended path forward, incorporating targeted incentives and optimization strategies to benefit producers, consumers, and the environment while balancing viability. The model entails that the government accepts part of the green hydrogen production in place of financial fees and redistributes this hydrogen to local industries at subsidized prices. This scenario expects:

For the government:
- Reduce immediate cash obligations from companies while securing stable supply.
- Enhance energy security through hydrogen blending and create new revenue streams from industrial decarbonization.

For hydrogen production companies:
- Improve profits by guaranteeing demand through partial hydrogen payments to the government
- Reduce cash payments to the government, making investments in Jordan more attractive.

For local industries:
- Access to subsidized hydrogen makes it cost-effective to transition to green fuels.
- Encourage investment in hydrogen-ready infrastructure, positioning industries for the future low-carbon economy.

The development of a domestic green hydrogen economy would require careful consideration of several factors:

- Water allocation strategies, particularly given the concentration of production in Aqaba
- Infrastructure development for hydrogen transport from Aqaba to industrial users
- Policy frameworks to address the current regulatory gap regarding hydrogen as a fuel
- Economic incentives that consider existing long-term fossil fuel contracts
- Decarbonization strategies with broader industry

MEMR's proactive approach to developing regulations, incentives, and a clear roadmap is paving the way for market creation, investment attraction, and private sector engagement, positioning Jordan as a green hydrogen leader.

The report provides detailed analysis of these considerations to support evidence-based policy development for industrial heat decarbonization in Jordan.

1 Introduction

1.1 Energy in Jordan

Jordan, a country located at the crossroads of Asia, Africa, and Europe, faces significant challenges in meeting its energy needs. As a nation with limited domestic fossil fuel resources, Jordan has historically been heavily dependent on energy imports, making it vulnerable to global market fluctuations and geopolitical tensions. This dependency has not only strained the country's economy but also raised concerns about energy security and environmental sustainability [1], [2]. The key points characterizing Jordan's energy landscape include:

- Growing energy demand: Rapid population growth, urbanization, and economic development have led to a steady increase in energy consumption.
- Financial burden: Energy imports constitute a significant portion of Jordan's gross domestic product (GDP), impacting its balance of payments and economic stability.
- Environmental concerns: The heavy reliance on fossil fuels contributes to air pollution and greenhouse gas emissions, conflicting with global climate change mitigation efforts.
- Renewable energy potential: Jordan possesses abundant solar and wind resources, presenting opportunities for diversification and sustainable development.

In recent years, the Jordanian government has recognized the urgent need to transform its energy sector. The country is undertaking a significant effort to improve energy independence, strengthen supply security, and move towards a more sustainable energy mix [3]. This has led to the exploration of various alternative energy sources and technologies, including renewable energy and, more recently, the potential of green hydrogen. Memorandums of understanding (MOUs) have already been signed for the production and export of hydrogen [4], as for local usage this can fall into either industrial chemical feedstock (previously reported on by the German Energy Solutions Initiative of the German Federal Ministry for Economic Affairs and Climate Action (BMWK) through GIZ [5]) and as an industrial thermal fuel, the overview can be seen in Figure 1 [5].

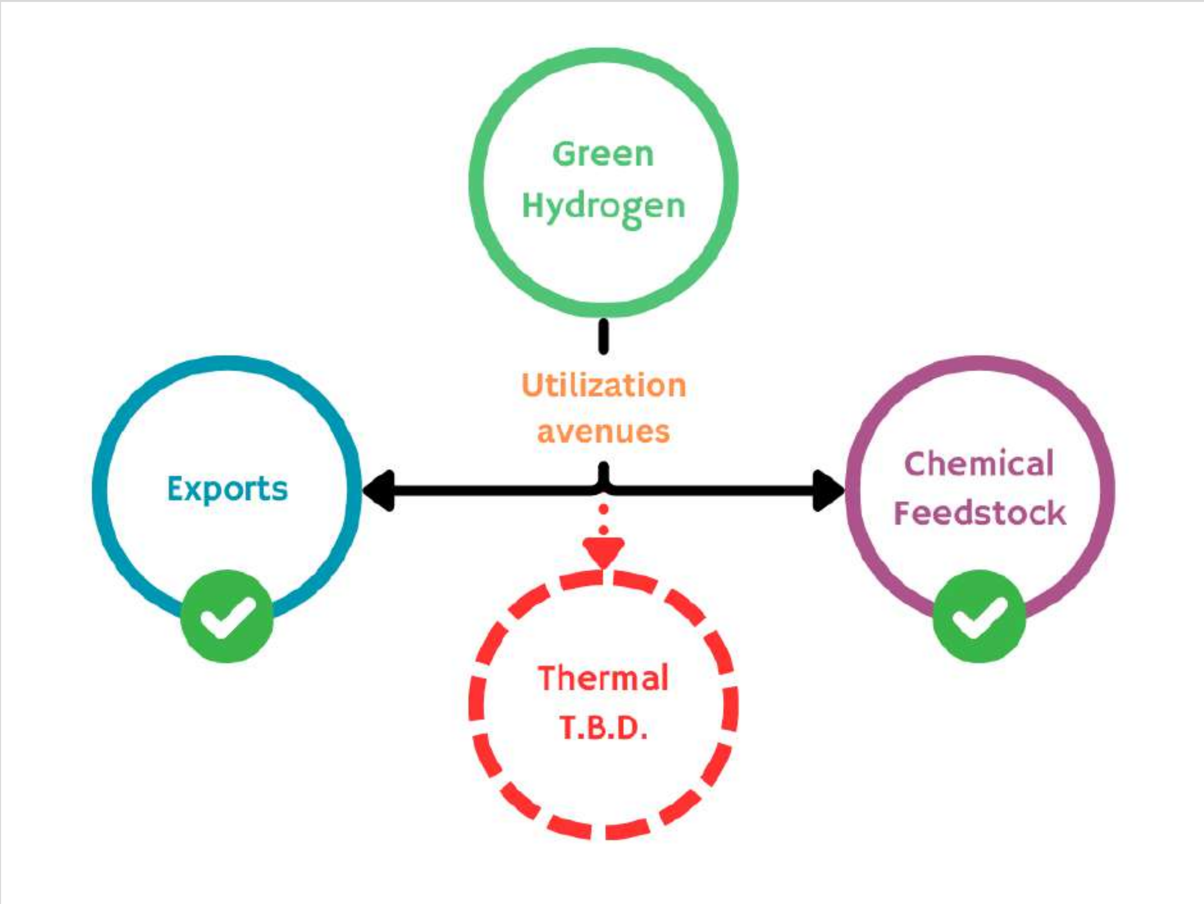


Figure 1 Ministry approach overview for green hydrogen in Jordan

As Jordan seeks to address its energy challenges and align with global sustainability goals, the exploration of green hydrogen for thermal processes emerges as a promising avenue. This report will explore the potential of green hydrogen as a thermal fuel in Jordan, assessing its feasibility, benefits, and challenges in relation to the country's specific energy landscape and industrial requirements.

1.2 Jordanian economy and industry

When it comes to the economic positioning of Jordan on the global stage, it is a country with a negative trade balance, where its imports exceed its exports, especially when this includes essential goods and raw materials. It is also worth noting that the government's public debt stands at about 101.5% of the total GDP as of 2022. The industrial sector in Jordan is therefore a huge part of the economy as summarized in Figure 2 [6].

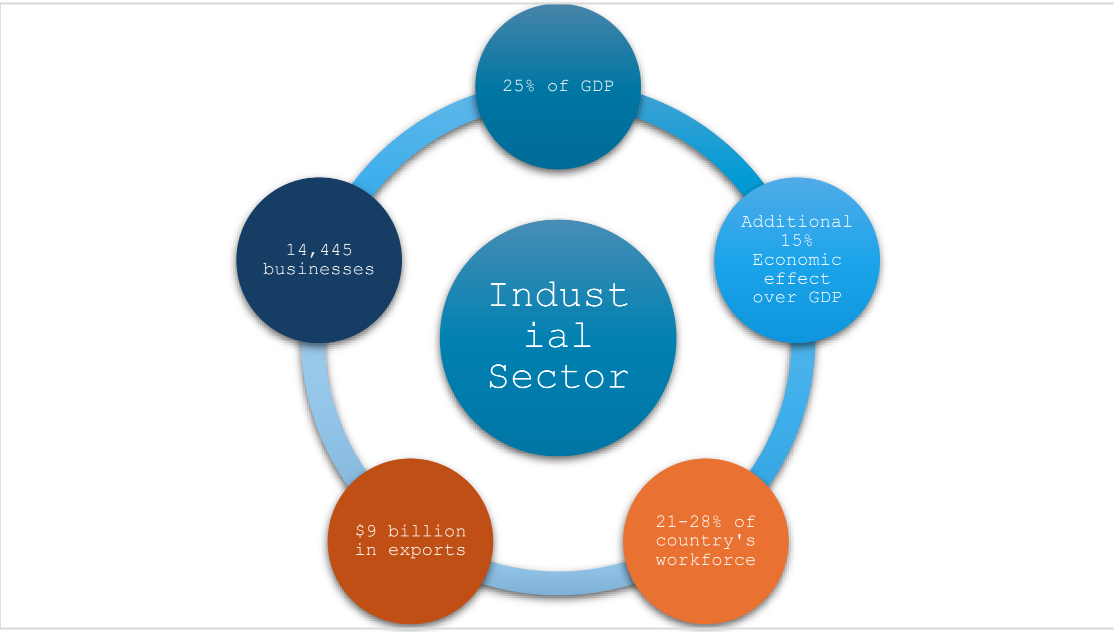


Figure 2 Major points on the industrial sector in Jordan

Jordan's industrial sector accounts for 25% of its GDP as of 2023, and it affects an additional 15% of the country's economy. The industrial sector employs about 262,000 professionals, which is 21% of the total Jordanian workforce (or 28% including the private sector), across 14,445 establishments. Industrial exports additionally supply the official foreign exchange reserve by about $ 9 billion annually and has seen a further 2% growth in 2024. A simple breakdown of the GDP can be seen in Figure 3. Manufacturing by itself accounts for over 25% of GDP as of 2023-2024, which is slightly below the record high of 2014 at 18.8% [6].

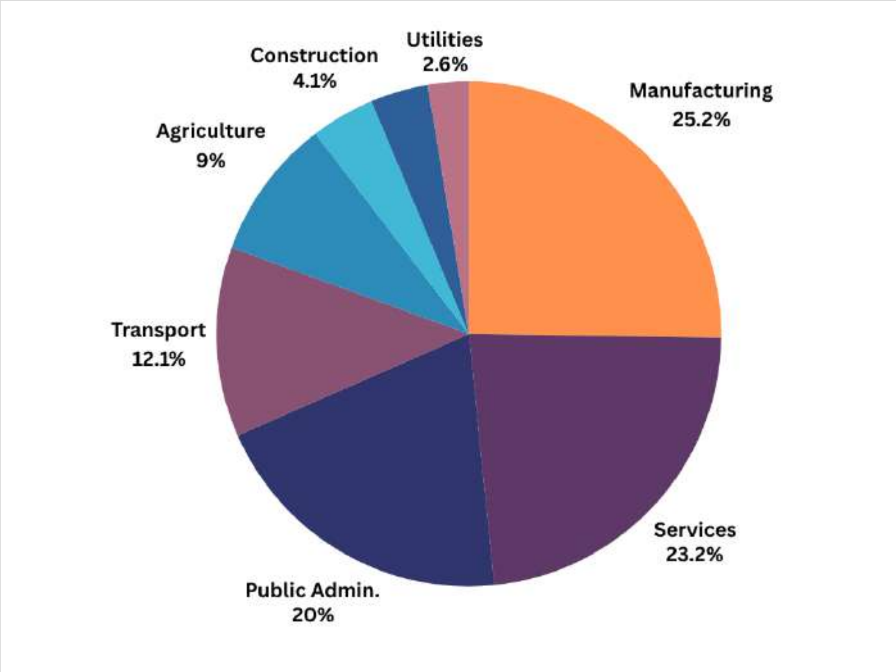


Figure 3 Jordan's annual GDP breakdown (2024)

1.3 Industrial sector

Jordan hosts a diverse set of industries officially divided into 10 key sectors; each of which is further subdivided based on specific work areas. The sectors and subsectors are presented in Table 1. The industrial sector is, primarily, divided into the manufacturing and mining industries. The mining sector, including phosphate and potash, contributed 9.12% to Jordan's GDP in 2021, generating 1.94 billion JD from extractive industries. The manufacturing sector added 1.16 billion JD from processing these resources, emphasizing their combined importance to industrial GDP and economic growth [7]. Within the manufacturing sector, key players include the food industry, which alone accounts for around 2% of Jordan's GDP, and the plastics and rubber industry, which contributes about 0.7% [8]. These industries still offer potential for further growth and development, potentially with the introduction of green hydrogen and other sustainable technologies [8].

Table 1 Industrial sectors in Jordan and sub-sector counts [6]

	Sector	Sub-Sectors	No. of establishments	employs	Exports ($million)
1	**The Therapeutic Industries and Medical Supplies Sector**	**11**	**139**	**9511**	**804**
2	**Chemical and Cosmetic Industries Sector**	**17**	**754**	**17424**	**1589.5**
3	**Engineering, Electrical and Information Technology Industry Sector**	**34**	**5154**	**39876**	**1213.6**
4	**Wood and Furniture Industries Sector**	**12**	**649**	**11391**	**23.6**
5	**Plastic and Rubber Industries Sector**	**13**	**1872**	**8077**	**339.2**
6	**Leather and Garment Industries Sector**	**15**	**988**	**72129**	**1870**
7	**The Food, Catering, Agricultural, and Livestock Industries Sector**	**24**	**2668**	**67067**	**1053.7**
8	**The Packaging, Paper, Cardboard, Printing and Office Supplies Sector**	**10**	**812**	**13125**	**300.7**
9	**Construction Industries Sector**	**11**	**2441**	**17411**	**150.1**
10	**Mining Industries Sector**	**3**	**92**	**8187**	**1724.8**

1.4 Hydrogen as a fuel

Hydrogen has a use beyond chemical feedstock, as a fuel. The direct combustion of hydrogen or use in a fuel cell for electricity generation are two ways to use hydrogen as an energy source or for energy storage. As a fuel, hydrogen can be used for heating buildings and transportation needs. However, the technology to use hydrogen as a fuel has yet to reach maturity and global distribution and access remains limited. Through direct incentives adoption is slowly ramping up. These incentive programs rely on the idea that replacing or blending with traditional combustible fuels would reduce carbon emissions worldwide, especially when compared to its closest rival: natural gas [9].

The exact amount of hydrogen consumed in Jordan is unclear. A recent study summarized that industrial consumption is about 8,900 tons annually [10], while another study mentioned that the consumption of hydrogen and its derivatives accounted for 289,248 Tons [11]. The former reports that among the hydrogen production methods are naphtha reforming (grey hydrogen) and fixed-bed platforming (a byproduct of gasoline enhancement). The latter study does not specify the production source but provides a breakdown of consumption: 93% is used in the fertilizer industry (270,606 tons), followed by the petroleum refining sector at 1.6% (4,628 tons). The remaining 5.4% (15,514 tons) is shared among the cement, chemical, steel, food industries, and power plants. [10], [11], [12].

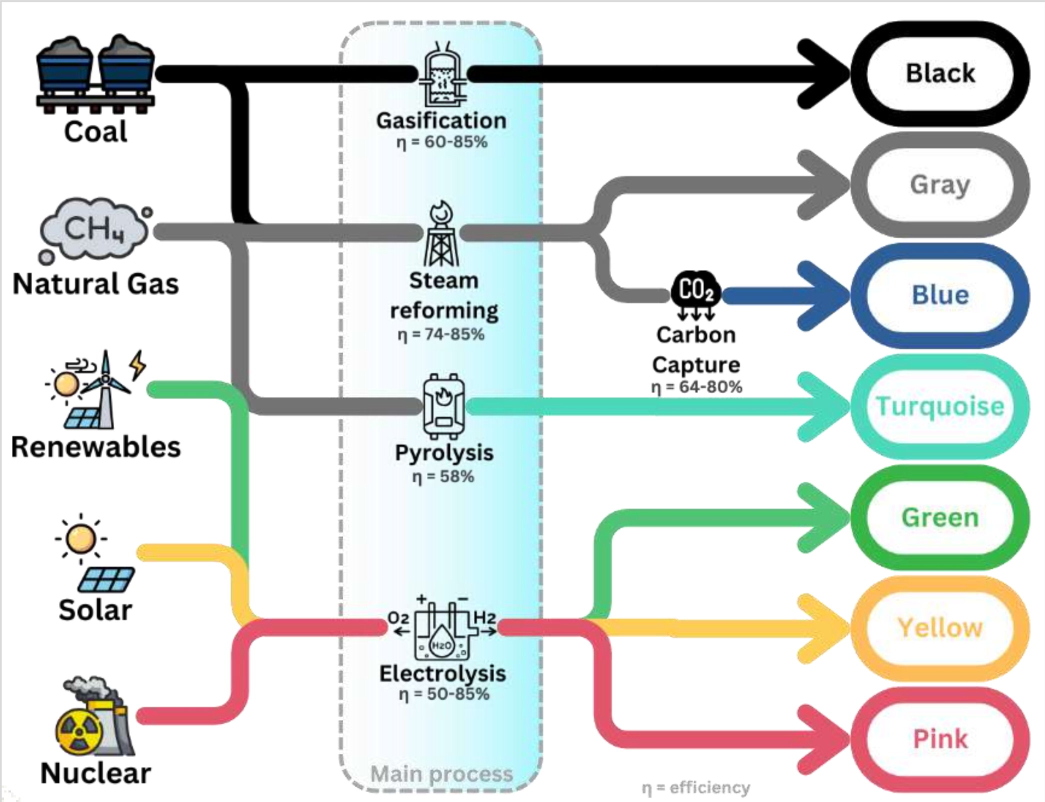


Figure 4 Hydrogen color classifications by energy source and main processes.

Hydrogen production methods, as demonstrated in Figure 4, suffer significant energy losses. Gasification has an energy efficiency between 60-85%, while steam reforming has an efficiency of 74-85%. Both methods produce high levels of pollution, and if carbon capture and storage is included to reduce it then the energy efficiency would decrease by 5-14%. Pyrolysis has a low efficiency of approximately 58%, while green hydrogen performs better at 70-85% in industrial use-cases [13], [14], [15], [16], [17], [18].

1.5 PtX

In 2015, the Paris Agreement on combating climate change was adopted during the 21st Conference of the Parties (COP 21) to the United Nations Framework Convention on Climate Change. The agreement aims to limit the rise in global average temperature to well below 2°C above pre-industrial levels, with efforts to further restrict the increase to 1.5°C, acknowledging that this would greatly reduce the risks and impacts of climate change.

To meet these targets, global greenhouse gas (GHG) emissions must be significantly reduced, with a particular focus on energy-related carbon dioxide (CO2) emissions. Recent reports from the IPCC (2020 and 2022) emphasize that achieving the 1.5°C target requires halving CO2 emissions by 2030 and reaching net-zero globally by mid-century or earlier to prevent the most severe impacts of climate change. In response, many countries have enhanced their climate mitigation goals, committing to achieve carbon neutrality by 2050 or sooner.

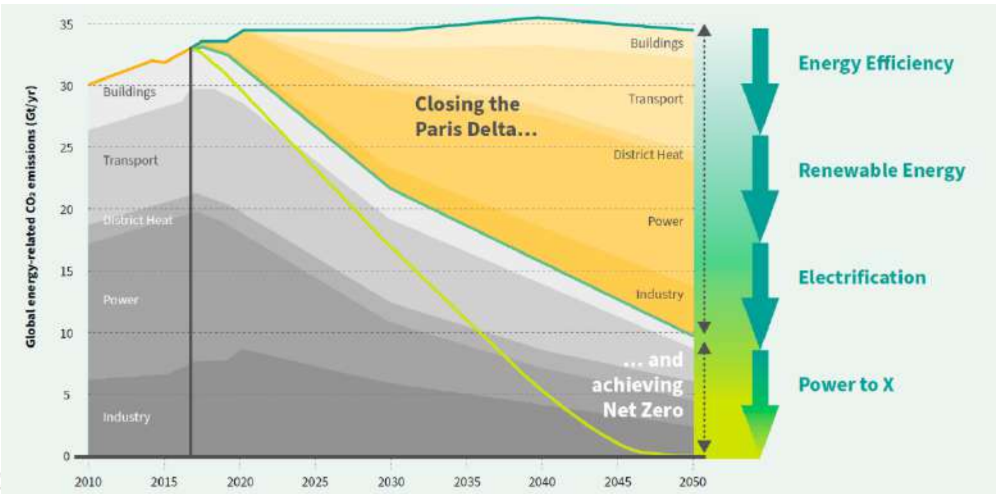


Figure 5 Global CO2 emissions, Paris Delta and Net Zero [19]

Figure 5 highlights the immense challenge of achieving the Paris Agreement goals. All sectors of the global economy must contribute to bridging the gap between a "business-as-usual" scenario, where CO2 emissions remain nearly stable, and a pathway of substantial reductions aligned with the Paris commitments. Addressing this "Paris Delta" requires four key transitions, represented by the downward arrows in Figure 5: (1) energy efficiency, (2) renewable energy, (3) electrification, and (4) Power-to-X (PtX) technologies. The transitions must be pursued rapidly and simultaneously, as the first three alone will not suffice.

To achieve a climate-neutral, net-zero world, the fourth transition—defossilization through PtX processes and products—must be significantly accelerated. PtX encompasses a broad range of sustainable fossil-free fuels and feedstocks (S4F) that are essential for eliminating greenhouse gas emissions in sectors of industry and transport that remain challenging to electrify. In these areas, the integration of green molecules, alongside green electrons, is crucial to closing the remaining gaps and meeting global climate goals.

The process of using electricity to power the production of a useful product of any kind is now known as "Power-to-X" or PtX. The "X" component can represent gases like methane and ammonia and the resultant moniker would be power-to-gas. Similarly liquid fuels like methanol are dubbed power-to-liquid, chemical industry raw materials would be power-to-chemicals, and it simply depends on the classification attenuated to the final product [2].

Going a step further, PtX can itself be designated "green" if the source of energy is a renewable source, and this extends to the entire value-chain of derivative products. Green hydrogen and Green PtX are the alternatives promising to decarbonize industries where they can fit into. Once integrated into existing/new industrial processes, green hydrogen also presents an opportunity to store excess renewable energy for later use. If it is already a component or byproduct of an existing process, it greatly improves the economic viability of hydrogen as a storage solution [20], [21].

1.6 Hydrogen for the industrial sector

Hydrogen holds significant potential as a heating solution in industrial sectors requiring extremely high temperatures exceeding 400°C, such as steel and cement kilns. When produced using renewable electricity, hydrogen can play a vital role in decarbonizing these hard-to-electrify processes and substituting fossil fuels in specific applications. This makes it a strategic resource for enhancing energy security, particularly in industrial sectors in regions like Jordan.

While electrification and heat pumps are ideal for residential heating, hydrogen complements these technologies by addressing the unique demands of high-temperature industrial processes. Raising awareness of their complementary roles, rather than framing them as competing solutions, is critical for achieving a balanced and sustainable energy future. Strategic investments can further clarify the capacity and feasibility of hydrogen in these specialized applications, supporting its integration alongside electrification.

By 2030, the global production of hydrogen is expected to be 5 Mtpa at a competitive cost with unabated fuels and a further 12 Mtpa at a cost of approximately 1.5 USD/kg hydrogen [22].

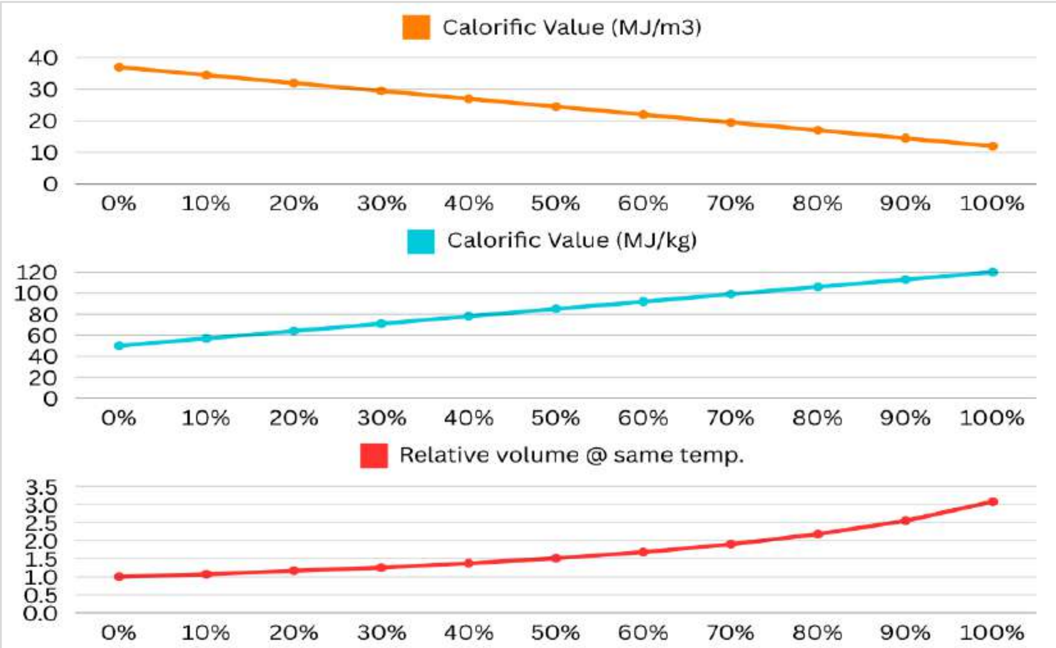


Figure 6 The changes in calorific value by hydrogen volume and mass in the mix followed by the relative volume requirement to maintain a certain temperature

Hydrogen's calorific value by mass is higher than natural gas, however, the density under the same conditions is lower. A 20% hydrogen mixture by mass would improve the calorific value of the fuel mix, however, by volume the 20% would decrease the calorific value of the fuel mix. The also means that while maintaining pressure conditions, maintaining a fixed calorific value would require a higher overall volume to account for the lower density of hydrogen. Figure 6 shows the effects of adding hydrogen to natural gas in different amounts [23].

Conversion to hydrogen in combustion processes requires multiple adjustments to the equipment and potentially subsequent processes. Hydrogen burns hotter than natural gas, the flame properties are different, the air requirement is different, and the byproducts from burning are different. The density difference may require a higher volume to be pumped, or operational pressure be higher with adequate equipment tolerance. The byproduct difference may require process adjustments – like in the cement industry where ash is accounted for in the final mixture – and require other additives to be introduced into the mix. The presence of water in the byproduct may also introduce issues in use-cases that are moisture-sensitive like the paper industry. Other considerations can be seen in Table 2 [24], [25], [26], [27].

Table 2 Potential adjustments to industrial equipment for hydrogen use

Industrial Furnaces & Kilns	Gas Turbines
Flame temp. adjustments (H2 burns hotter)	Fuel injection timing modifications
Air-fuel ratio recalibration (H2 needs less air)	Compression ratio adjustments
Burner geometry modifications	Combustion chamber temperature controls
Flow meter recalibration (H2 different density)	Flame detection systems recalibration
Safety sensor thresholds adjustment	NOx emission control calibration
Combustion monitoring system updates	Fuel/air mixing systems adjustment

If I may kindly request to conclude this chapter with the detailed report objectives to introduce and justify the methodology developed for this assignment.

The objective of this report is to ascertain the potential demand for hydrogen for combustion-based processes in the industrial sector and the pathway to fulfillment which includes potential challenges. This requires an understanding of what these processes are and their current energy demand as well as their potential for hydrogen substitution. The next section walks through the proposed methodology. It begins with the effort to repurpose existing industrial energy audit reports for the context of this investigation in combination with walk through audits at target high-potential facilities – considered according to the global trend for similar schemes [22]. Further feedback from regulatory or industrial facilities may provide additional information and feedback to inform about data-scarce parts of the industry such as those potentially not covered by the accessed energy audit reports or other reports. To facilitate the in-person data gathering activities, a standardized questionnaire is proposed to assist in comparative analysis with other reports from different sources.

2 Methodology

This section outlines the approach for assessing the potential of green hydrogen for industrial process heating in Jordan.

2.1 Information gathering and objectives

The goal is to identify the industrial sectors with the highest potential in terms of both thermal energy demand and high temperatures. The potential for hydrogen and green hydrogen in Jordan's industrial sector can then be ascertained. The first step is to gather data and information. The first point to keep in mind is that not all thermal processes are relevant to this study, only those that operate at high temperatures achieved through combustion are deemed relevant. Low temperature processes will always be better served by direct electrification, such are the limitations of energy conversion efficiency. The target thermal processes run at temperatures north of 500+ °C. The main data sources and formats are shown in Figure 7.

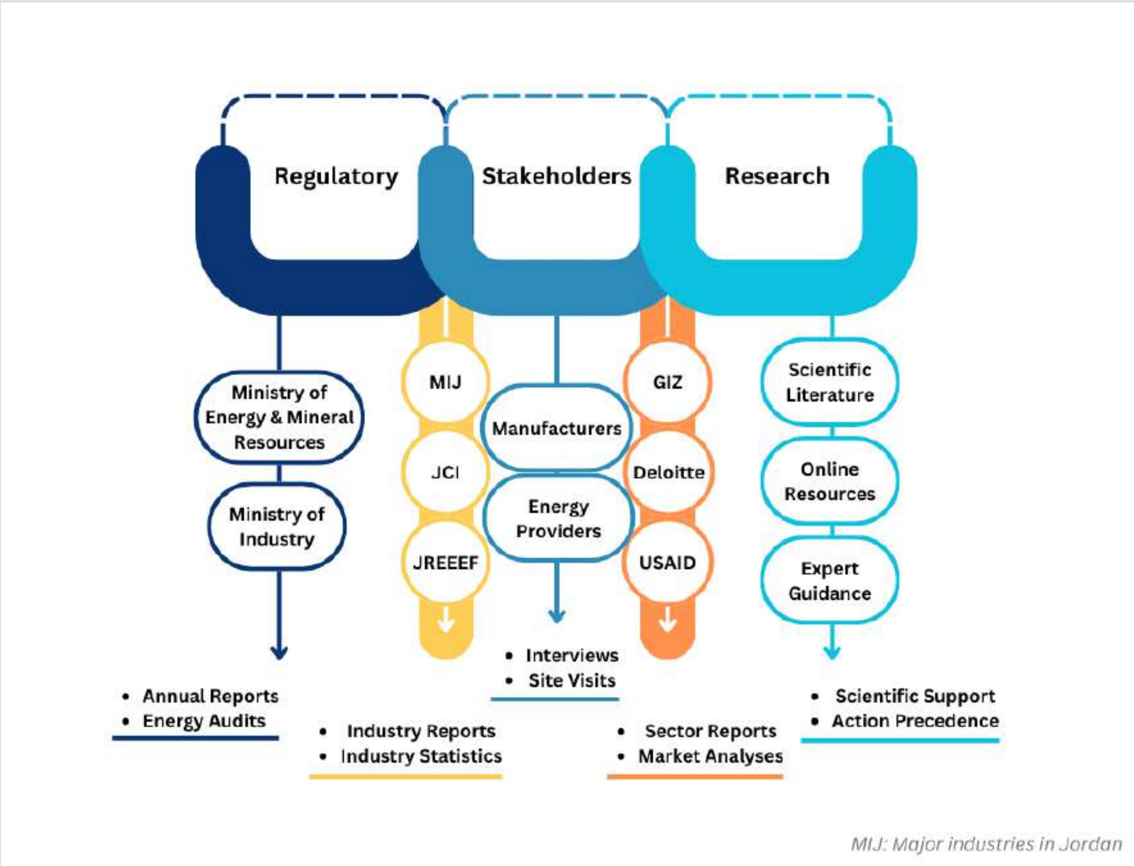


Figure 7 Data Collection Sources

2.2 Standardizing data gathering

To formalize and standardize the data gathering process across the different modalities and sources, a specific set of objectives has been set. The objectives set for organizing and analyzing the data and information gathering tasks are as follows:

- Are the manufacturers aware of green hydrogen as a thermal fuel alternative and its potential in their given industry?
- What are the manufacturers' current energy efficiency practices and their impact on their economics and bottom line?
- Are there any high-temperature thermal processes that fit the profile for hydrogen substitution or blending?
- Will any of the suitable processes be changed, reduced or expanded soon?
- Where and how could green hydrogen play a part as a thermal fuel in the expansion of the manufacturer's current production capacity?
- Are there any current green schemes or clean-energy incentive programs which the manufacturer is benefitting from?
- Is the manufacturer willing to invest in on-site hydrogen generation or would rather purchase it ready from a nationally backed source?
- To get an idea of how much hydrogen would end up being required in a future scenario where financial feasibility was met.
- To understand the impact of current fuel and energy pricing on the future of the given industry in Jordan.
- To ascertain what the understanding and receptiveness of hydrogen is at each company and what barriers and incentives could stand in the way of its adoption.
- For all the information given, are you the standard-case for the local and regional industry in terms of energy practices.

Following the analysis a comprehensive list of all companies and their data should be provided along with the coverage of each given industry in terms of count to energy footprint. The analysis should result in the ability to perform the next set of tasks which are:

- Review the regulatory framework that directly and indirectly affects all stages of green hydrogen production, storage, transport, and consumption.

- A market review for available green hydrogen electrolyzers, storage tanks, piping network, and boilers.
- The development of a techno-economic model for the evaluation of green hydrogen production in Jordan. This model considers the available solar energy potential, water availability, technology availability and readiness.

2.3 Energy audit analysis

To ascertain the thermal needs of Jordan's industry, data needed to be gathered and analyzed on the way the industry consumed fuel and electricity, and for what purposes. The Jordanian Ministry of Energy and Mineral Resources (MEMR) has already implemented a scheme to promote and facilitate energy efficiency across the entirety of the industry. The ministry supported the execution of energy audits for several factories in Jordan through Jordan Renewable Energy and Energy Efficiency Fund (JREEEF). As a result, JREEEF possesses many completed energy audits conducted over the course of the previous five years.

While the audits were not identical in scope, they did provide an approximate representation of the industries included. Another thing to note is that for the purposes of this report, which is an assessment of high-temperature thermal use-cases, the reports did not always contain specific information regarding process temperatures and so the fine granularity of specific machinery replacement by a hydrogen-powered counterpart cannot be provided. The analysis process is to categorize and group the thermal demand and use cases within each industry. Wherever explicit information on the operating thermal demand is unavailable, other data such as fuel type, fuel consumption, energy rating, industry/sub-industry and machine count is used to extrapolate a potential range of operation. Where the confidence of the extrapolation is weak or produces anomalous results, it is discounted from the final count of facilities that have provided thermal demand related information within their energy audit reports.

2.4 Questionnaire

Interviews and site-visits were conducted to gather information about each of the respective target establishments. A set of objectives were determined for the overall activity, and this resulted in three forms of information gathering or three steps: a questionnaire built on the objectives as a framework for the information being gathered, site-visits and interviews with stakeholders and their representative offices where site-visits were not possible.

The questionnaire developed is a framework to build on and gather information pertaining to a given company and understand its exposure to green hydrogen and its current and future integration feasibility. A copy of the questionnaire is available in Appendix H. The sections were built in accordance with the desired objectives previously listed, and have thus been divided into the following sections in the questionnaire:

- Awareness of & interest in green hydrogen
- Current energy efficiency and heating processes
- Future heat demand and anticipated changes
- Technical and economic feasibility
- Sustainability and environmental impact
- Onsite hydrogen generation
- Timeline and implementation plans
- Monitoring and evaluation
- Barriers to adoption
- Recommendations

2.5 Site visits and interviews

The site visits, or walk-through audits, are conducted as a way to discuss directly with the stakeholders on the status of their manufacturing establishment. It is important to note the impact of Jordan as an industry's economic environment, the challenges and barriers associated with energy, how it is affecting current production, and the outlook of the respective manufacturer. A manufacturer's outlook on their local industry as a whole from a regulations and legislative viewpoint with a focus on energy is also of note.

Some highly sensitive and large industries are not as easily audited, not to mention how the data can be considered highly sensitive, these were the main targets of the site visits. Performing on-site visits is a way to engage directly on the topic of this report. The goals of the visits - where possible - were to perform a walk-though audit of the respective facility and determine if there are any high-temperature processes to be targeted. If an adequate thermal process was identified it would then be analyzed for how and where green hydrogen can be a viable substitute for whichever fuel is currently being used. This is, of course, disregarding whether the fuel is economically viable, whether it is technically viable, and technically feasible to transition to if deemed viable.

Where the actual manufacturing site could not be visited for any reason, an interview was conducted with stakeholders instead of at a representative office. The interview followed the same structure as the questionnaire to cover the same set of objectives. In large part, the interviews took the same pattern and resulted in the same conclusions as the site visits.

To standardize the findings during each of the site visits, the questionnaire was used as a guide throughout the interactions, where a successful visit is one where the main objectives – as targeted by the questionnaire – were sufficiently answered. Heavy industries are not able to fully divulge their or their competitors' figures but were cooperative enough to provide figures and ranges for their operations and the broader Jordanian market.

Beyond the audits and visits, comprehensive research and analysis of reports and documents produced by other relevant organizations were conducted and analyzed to gather data and information. This research incorporated annual reports, sustainability reports, news publications, and other sources containing quantitative data that is relevant to the industrial sector and target companies. Analyzing all the available resources helps in building a wholistic overview of the industrial sector and its sub-sectors, including their energy demands for thermally intensive processes.

3 Data and Analysis

3.1 Stakeholder feedback

Field data and stakeholder engagement revealed varying levels of readiness and distinct priorities across key institutions. The Ministry of Energy and Mineral Resources (MEMR), leading this analytical effort, has prioritized the assessment of potential hydrogen capacity, and is actively coordinating with multiple agencies to develop comprehensive estimates. Notable gaps were identified in the regulatory framework, particularly in the Energy and Minerals Regulatory Commission (EMRC)'s current policies which lack specific provisions for hydrogen as an energy carrier. The Ministry of Environment's (MOE) regulatory framework similarly shows an absence of hydrogen-specific considerations, indicating a need for policy alignment.

The Jordan Chamber of Industry (JCI), representing industrial stakeholders, has emphasized that economic viability and sustainable fuel reserves post-transition are paramount concerns that must be addressed in any hydrogen implementation strategy. On its own, it is pushing forward auditing and transparency of energy use, consumption, and efficiency across the industrial sector which directly affects the implementation of any fuel-transition or promotion strategies.

Educational institutions play the role of expertise, sustainability of knowledge and maintenance for the future. Major universities are already teaching and training engineers on hydrogen as an energy carrier. These universities are the University of Jordan, the German Jordanian University, and AlHussein Technical University. These efforts and foresight prepare the workforce required to adopt, transition and maintain local hydrogen capacities, facilities, and operations.

3.2 Major Industry Reports and other publications

From energy reports, sustainability reports, websites, news articles, and online resources, the following documents were consulted to gather comprehensive information on current energy consumption amounts and trends. [Confidential]

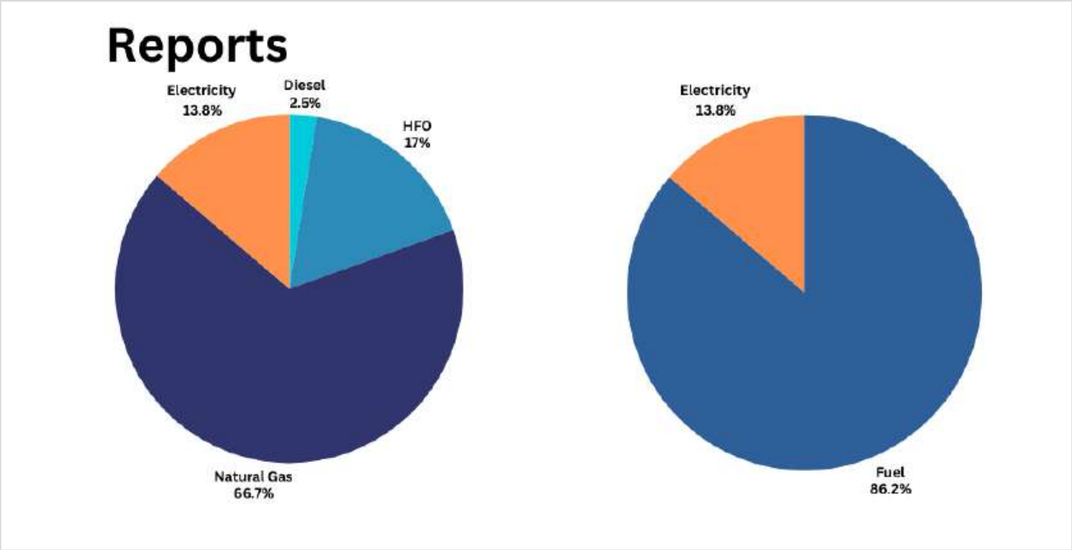


Figure 8 Energy consumption analysis by fuel from analyzed reports

3.3 Energy audits

The energy audits granted access to by JREEEF included companies and manufacturers from 9 out of the 10 industrial sectors. The audits contained companies from the medical, chemical, furniture, plastics, textiles, paper, food, construction, and lastly mining sectors. Most of the sectors were found to use low to medium temperatures except for a few that use temperatures as high as 1700 °C, and 1200 °C for combustion-based processes. These high temperatures belong to the steel melting, and cement kiln temperatures (the gas temperature for the process can reach 1700 °C). Figure 9 and Figure 10 show the maximum temperature and temperature ranges reported, respectively. The energy audits were conducted in the following manner:

- Preparation: Initial site survey with operational and maintenance staff, identifying data needs, and inventorying production lines and utilities.
- Data Collection: Using tools like power analyzers, clamp meters, and temperature loggers to measure energy consumption, surface temperatures, and equipment efficiency.
- Data Analysis: Calculating key performance indicators (KPIs) such as energy usage and cost indices, identifying inefficiencies, and proposing energy-saving measures.

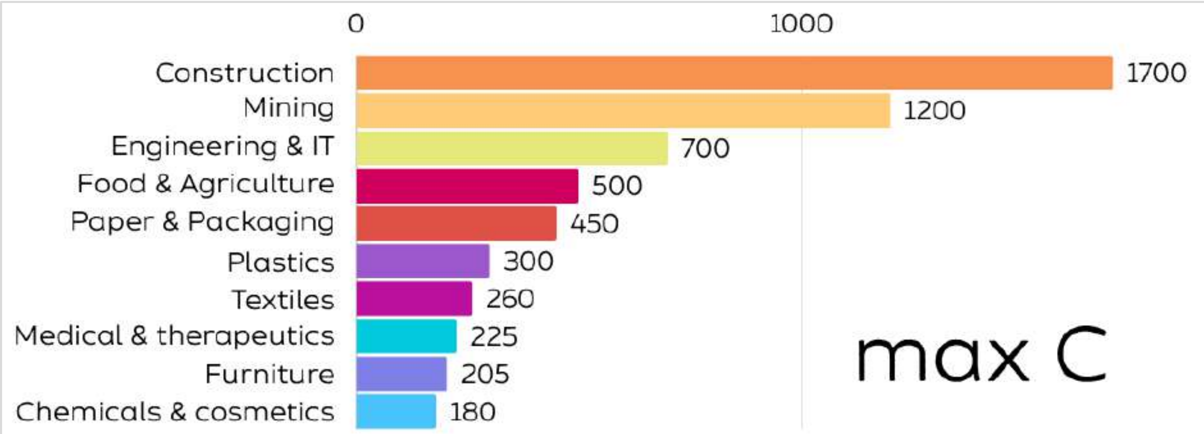


Figure 9 Audited industries and the maximum process temperatures observed

Each member of the industry is responsible for their own equipment, it is therefore complicated to attach a specific fuel to a temperature range, however, the general trend can be ascertained. The lower end of the temperature scale for industrial processes is catered to with electricity and LPG. The specific functions and equipment greatly vary in this range but maxes out at about 400 for LPG and 550 for electricity in the food and agriculture industries for boilers, ovens, and fryers. Stepping up in the temperature range the fuel shifts to diesel and HFO topping up at 1200 °C each for the cement and steel industries. Beyond this point were coal and natural gas used in the clinker preheating and melting processes in cement manufacturing which operate at a flame temperature of about 1200 and 1700 °C respectively. The ranges observed for each industry can be seen in Figure 10.

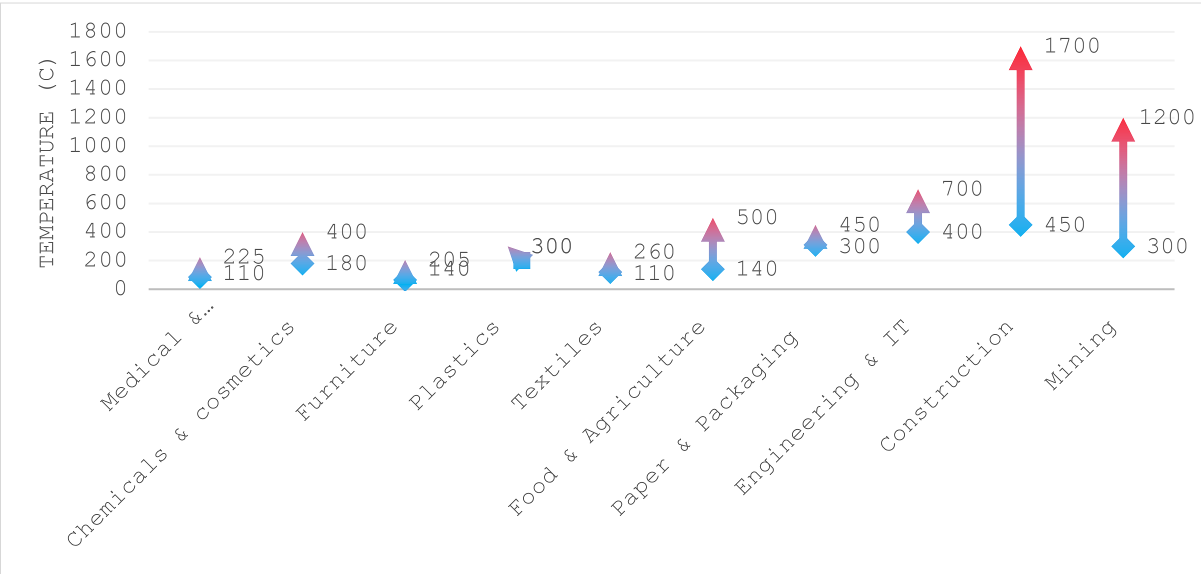


Figure 10 Audited manufacturers' operating process temperature ranges

The following graphs present a comprehensive summary of the findings of the energy audits conducted across various industrial sectors in Jordan. The pie charts below in Figure 11 highlight the percentage of each energy source used in industries. Electricity makes up about 59% of the total energy source, while diesel is the most used fuel at 17%.

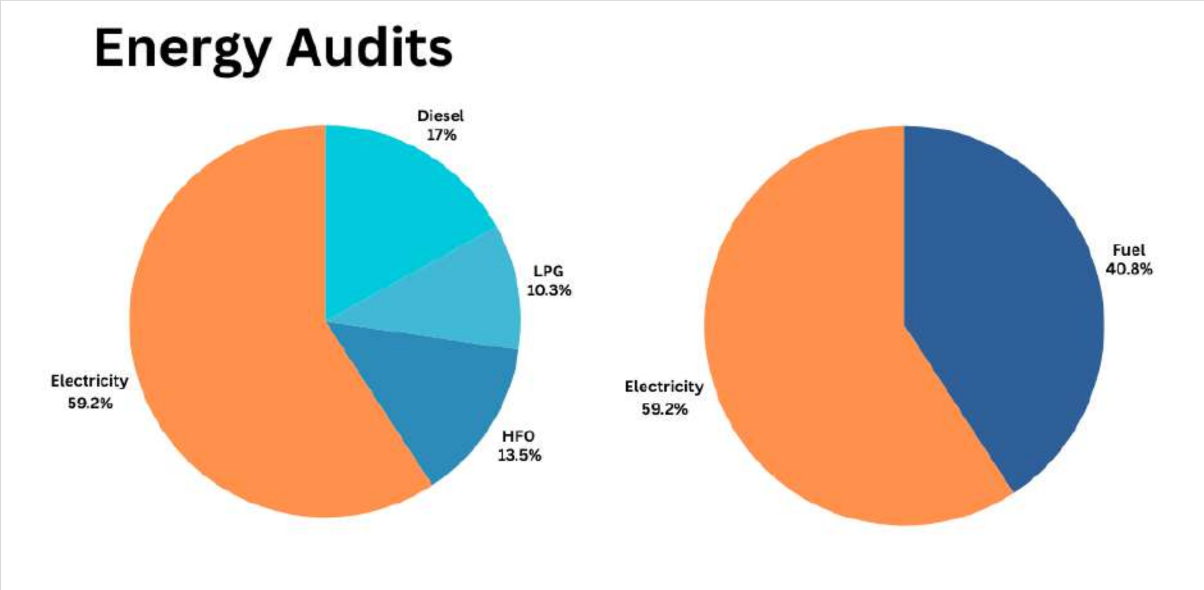


Figure 11 Energy consumption analysis by fuel from audits

3.4 Targeted industry

3.4.1 Site visits and interview data

Based on the energy audits, specific target industries were set-aside for their high temperature and thermal energy requirements. These target industries are construction, mining, and paper & packaging. Site visits and walk-through audits were conducted in five manufacturers in potash & bromine, iron & steel, paper, ceramics, and cement industries as shown in Figure 12. Each visit began with an interview and tour plan. During the interview, the awareness of each manufacturer on the topic of green hydrogen was assessed. Nearly all of them were already aware of it as a fuel source, however, few were aware that their current infrastructure could support a partial transition by blending natural gas and green hydrogen, which is a notable finding. A manufacturer is always interested in upgrading their technology so long as it doesn’t negatively impact the bottom line of the establishment. The results from the visits are shown in Figure 13.

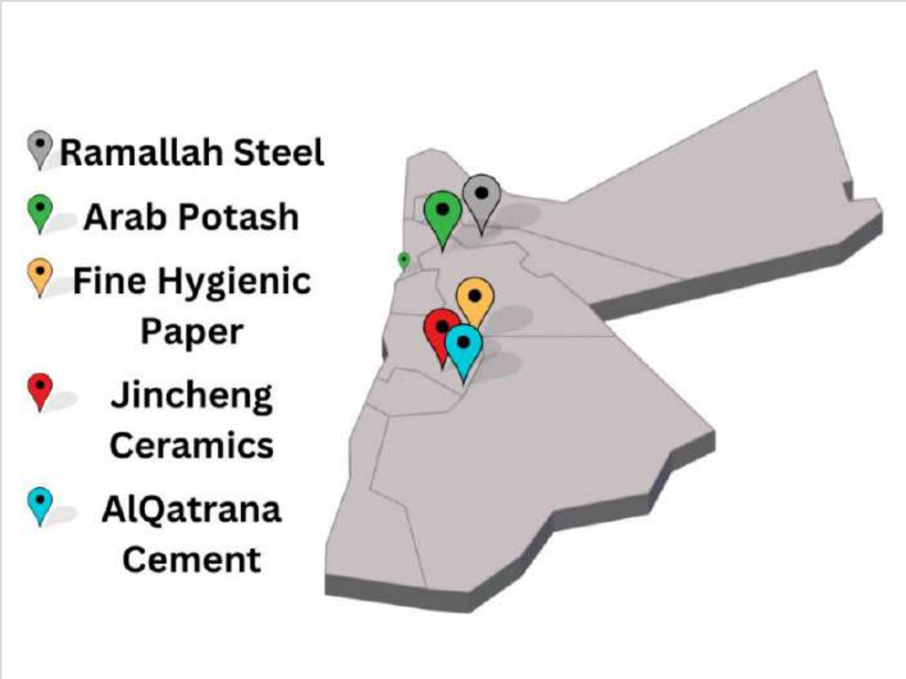


Figure 12 Site visits to manufacturers and locations during the study

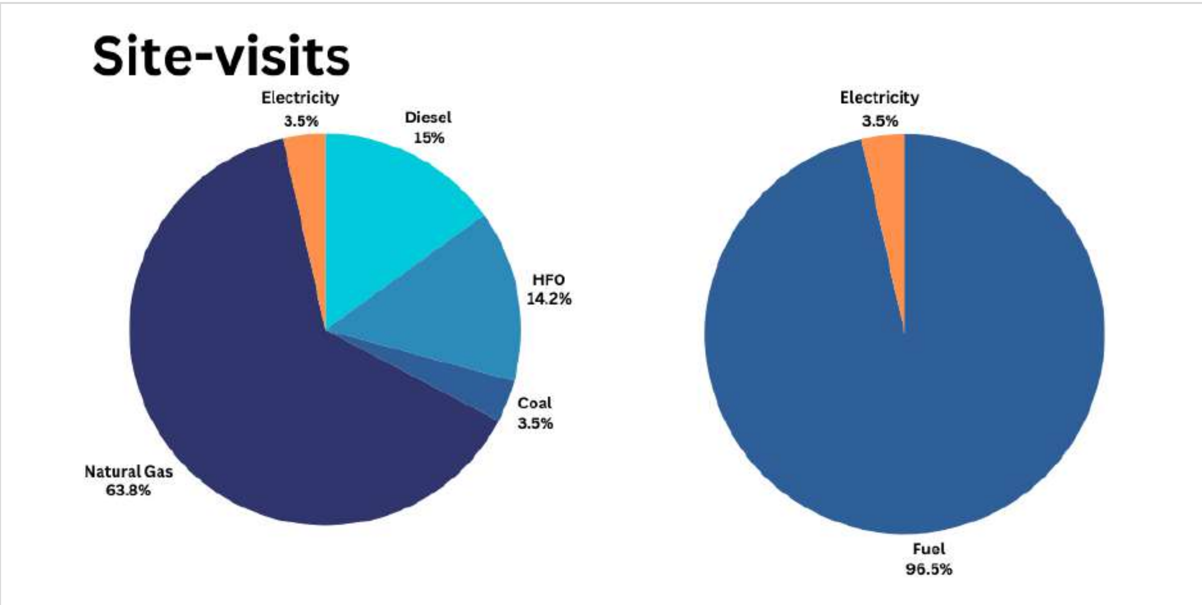


Figure 13 Energy consumption analysis by fuel from site visits, walk-through audits, and interviews

Most of the manufacturers who were visited, particularly the largest, already operate with high efficiency, driven by private energy audits. This is largely due to Jordan's high energy costs, which impact their competitiveness both locally and regionally. Compared to oil-producing neighbors where energy prices are significantly lower, Jordanian manufacturers face considerable challenges in staying competitive.

The observed manufacturing lines all tried to utilize byproducts, waste products and heat back into the process to improve the efficiency and economic margins of the establishment. This means that introducing hydrogen must meet the same or improve the manufacturers standing in terms of energy efficiency as well as waste output. In a world transitioning to clean and green technologies, increasing the waste output is highly unfavorable and could potentially limit access to certain markets.

An important aspect to check when it comes to efficiency is if any of the processes currently in use could potentially benefit from hydrogen as a substitute or as part of the input fuel mix. Some relevant processes were notably absent in the Jordanian market, which goes back to the economic situation and the tight margins required to stay competitive against regional competitors. This point reiterates how green hydrogen needs to meet efficiency targets compared to whichever fuel is currently being used, as it is likely already the most efficient option available for the given process.

Most of the establishments visited either maintaining their current production levels or were in decline due to the increasing competition from external players. This is directly impacted by the country's energy costs and the layers of tariffs – constantly changing – that are imposed. For instance, it was found that the entire glass production sector has left the country due to rising energy prices, an issue that was not addressed by the government. This loss of regulatory support led to an industry shutdown, opening the market to imports from other locations. As a result, thousands of jobs were lost, and the country now faces a significant issue in managing and disposing of glass and glass-containing waste, which has been accumulating since the industry shutdown.

Most establishments visited would not be averse to maintaining their own on-site hydrogen production facility; however, in almost all cases, this is not a realistic option. Water scarcity, which already plagues many sites, would not allow the additional demand required for on-site hydrogen production. Many sites also struggle to obtain and run solar energy facilities. For solar capacity installations, there is a grid-parity rule – specific only to large consumers - where capacity is limited by grid-consumption. As these manufacturers try to localize their energy production, often their grid consumption is low compared to their requirements which limits their ability to obtain the necessary permits to expand towards electrification.

The chart in Figure 14 shows the information flow, data sources, and types of fuel used across the nine sectors covered by data collection. The graph in Figure 15 summarizes the consumption across all the sources. It can be observed that natural gas dominates the mining industry where it has been readily adopted. HFO holds most of the energy mix for the construction, textiles, and paper & packaging industries. The remaining industries rely heavily on electricity. For this study, the most scrutinized industries are those currently consuming fossil fuels and natural gas, as these are the most likely to employ them for high-temperature processes that could be replaced by hydrogen.

[Confidential]

Figure 14 Industrial energy consumption data sources

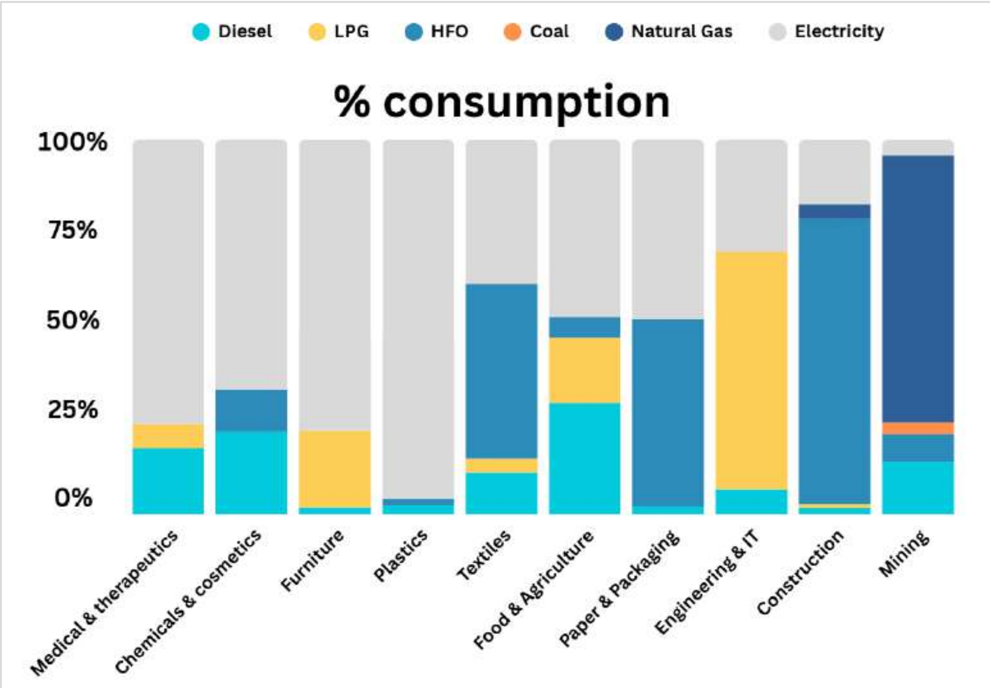


Figure 15 Energy consumption by source for the industrial establishments covered in this study

3.4.2 Thermal processes

After the site visits and walkthrough audits of various industrial facilities, we've developed diagrams illustrating the existing processes and the specific identified areas where green hydrogen can be used as a combustible fuel or in a fuel mix. Each illustration shows the production processes as nodes. If a process node is one where the represented process consumes hydrogen it is deemed as a potential target for hydrogen introduction. While hydrogen is currently utilized in some of these processes (bromine), there's significant potential to expand its usage capacity and potentially replace traditional fuels in thermal stages. Incorporating green hydrogen into these processes, we can significantly reduce greenhouse gas emissions and contribute to a more sustainable industrial landscape.

Hydrogen can partially or fully replace conventional fossil fuels in both the preheating tower and rotary kiln stages of cement production through modified burner systems. Hydrogen's higher flame temperature (around 2000°C) and velocity would require careful control and additional safety measures. It can be effective in providing the necessary heat for both preheating and clinker formation, however, considerations for water vapor from hydrogen combustion need to be considered. The implementation would involve upgraded burner systems with multiple injection points, enhanced monitoring systems, and careful management to maintain optimal temperature profiles and clinker quality. The process diagram is shown in Figure 16.

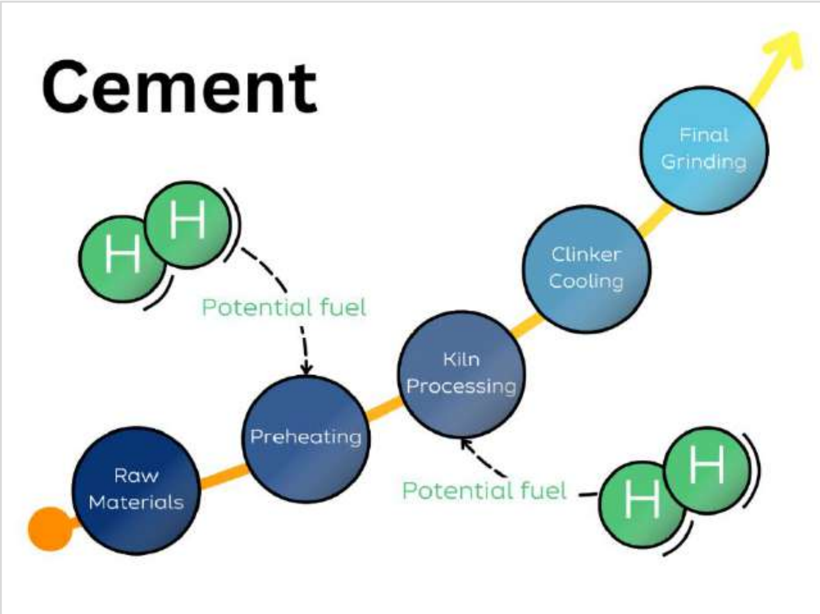


Figure 16 Cement production process + hydrogen potential

In steel manufacturers, the preheating process could support the partial or complete replacement of natural gas or HFO with hydrogen. The preheating process heat steel billets from room temperature to a working temperature of 1200-1250°C prior to the rolling process. A furnace that runs on multiple heating zones can be gradually converted to hydrogen/hydrogen-mix fuel. The different flame characteristics of hydrogen do require consideration and adjustment as well as the presence of water vapor produced during combustion to maintain the products quality. The process diagram is shown in Figure 17.

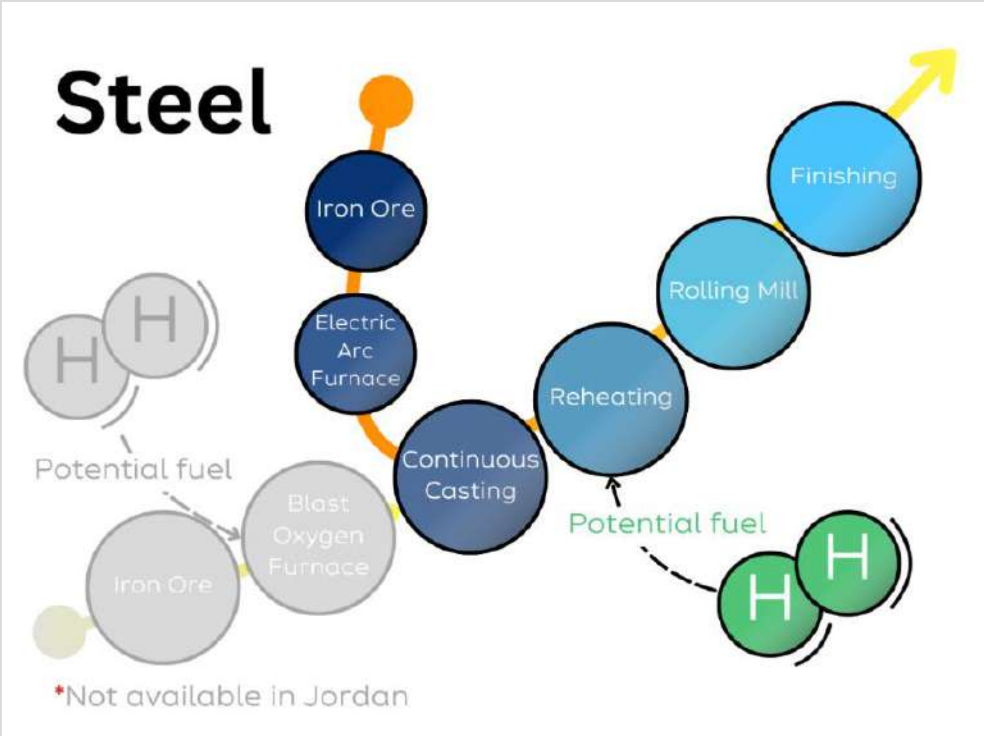


Figure 17 Steel manufacturing process + hydrogen potential

Two processes in the ceramics industry can benefit from partial or complete fuel replacement with hydrogen, these are the drying and firing processes (typically 1200°C). This would require that traditional systems be replaced with hydrogen-capable counterparts. The flame characteristics and humidity need to be carefully managed, especially in the dryer stage that's highly sensitive to moisture content in the exhaust gases. Specific modification would also be required in the burner systems according to hydrogen's combustion characteristics to maintain uniform heat distribution throughout. The process diagram is shown in Figure 18.

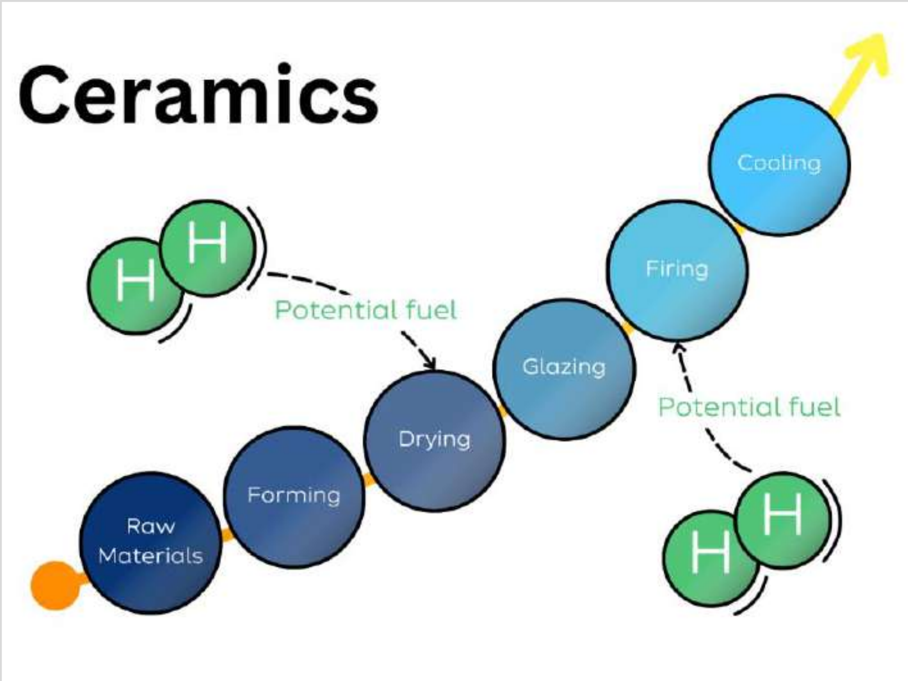


Figure 18 Ceramics manufacturing process + hydrogen potential

In the paper and packaging industry, hydrogen can be introduced as a partial or complete replacement for the fuel used in burners providing hot air for the paper drying process (Yankee dryers, typically 350-500°C). The equipment would require modifications catered to hydrogen combustion characteristics and to control and maintain proper humidity levels across the Yankee cylinder surface. The process diagram is shown in Figure 19.

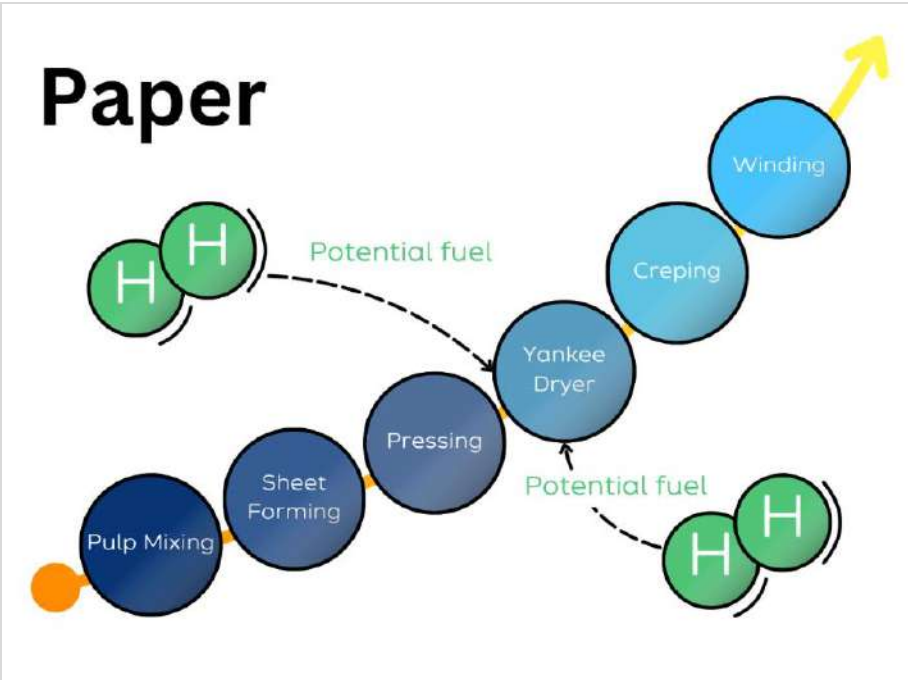


Figure 19 Paper/tissue manufacturing process + hydrogen potential

In bromine production, hydrogen can be integrated as a fuel substitute in either brine treatment or purification process, or both. The adaptation requires modified burner systems to handle hydrogen's unique combustion properties while managing corrosion risks in the environment. The moisture content of the exhaust must also be considered, although clean burning is an advantage. Safety considerations for the change must also be implemented. A small amount of hydrogen can be produced as a byproduct of secondary derivative processes in industry like the electrolysis of hydrobromic acid (HBr). The process diagram is shown in Figure 20.

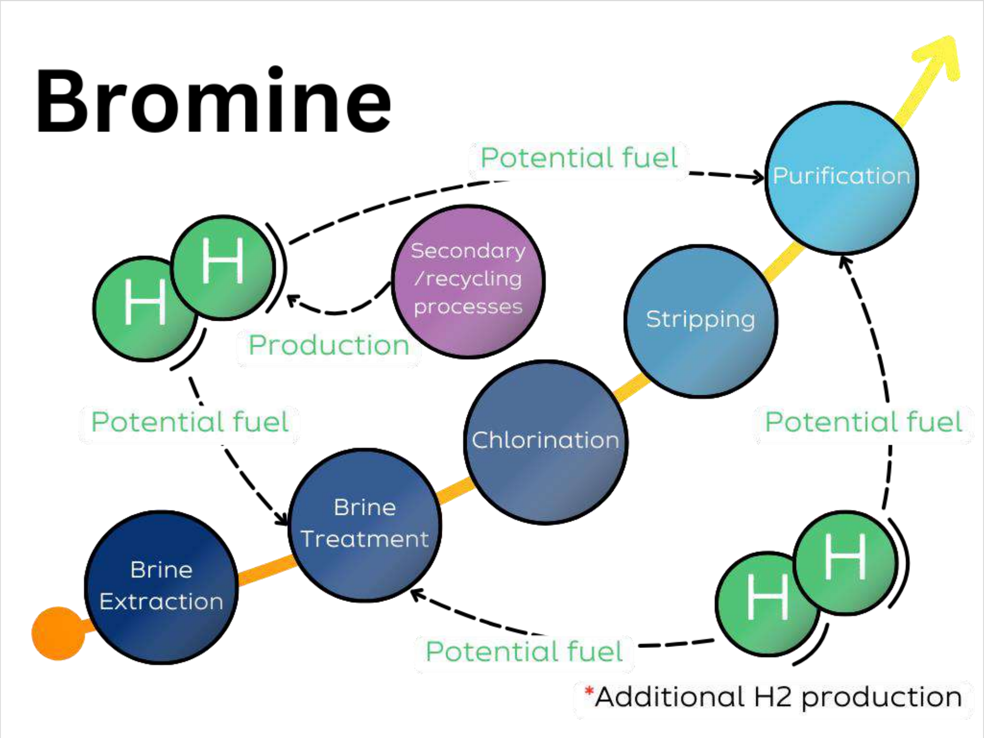


Figure 20 Bromine manufacturing process + hydrogen potential

3.5 Energy breakdown

Energy consumption analysis is crucial for understanding resource utilization and identifying areas for potentially using hydrogen in Jordan's industrial sectors. The following charts provide a comprehensive overview of energy usage patterns. These visualizations break down industrial energy consumption by fuel type (Figure 21), present findings from energy audits (Figure 22) and together, these charts paint a detailed picture of Jordan's industrial energy landscape and the coverage of this study.

The resultant hydrogen capacity estimates are shown in Figure 24 and Figure 25. In Figure 24 the capacity is based on the analysis of the data gathering and temperature range clusters with assumptions as shown in Appendix E. Figure 25 and

Figure 26 show the maximum hydrogen capacity that could be required by fuel type, suggested from what temperature range its client processes and industries come from. The impact order is a combination of the proportion of fuel found to be used to high thermal demand process and the ease of substitution of said processes. This combined approach also correlates with the impact of focusing on a given fuel in the conversion effort to green hydrogen from a relative standpoint. The high temperature hydrogen requirement from the analyzed dataset is approximately 59 ktons, under the total consumption extrapolation it is 145 ktons and the maximum potential capacity requirement for hydrogen - clustered by fuel type - in a complete replacement scenario is 223.4 ktons. The medium and low temperature clusters could benefit greatly from conversion to solar thermal technologies, a recommendation that is absent from many of the reports and audits analyzed.

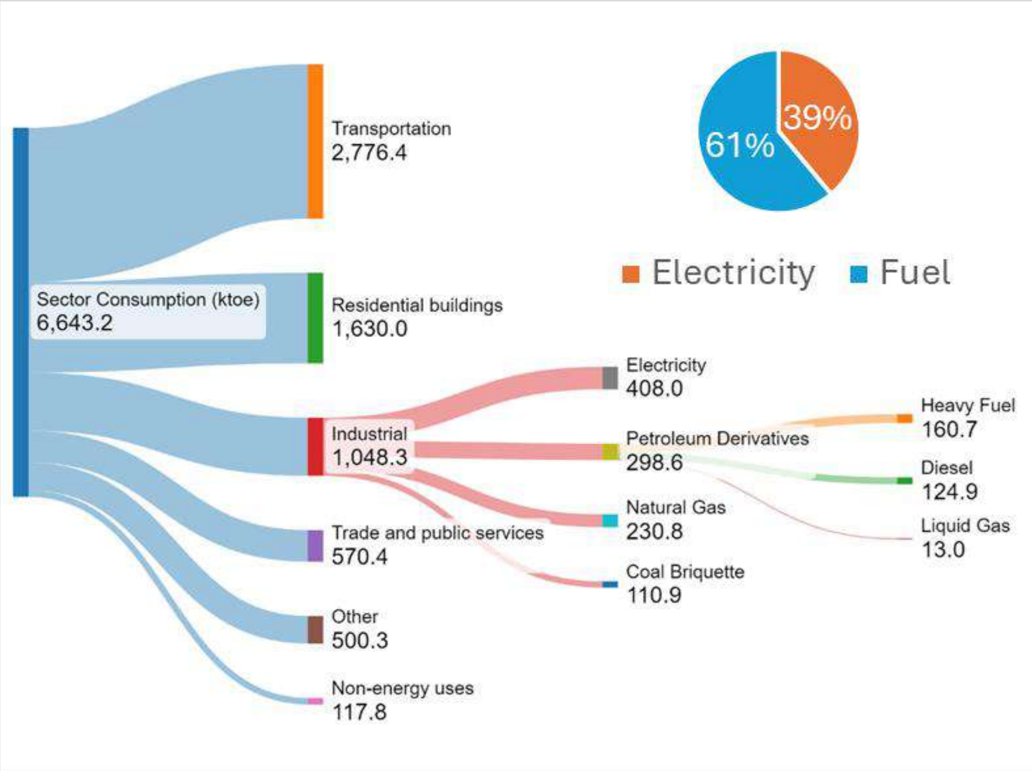


Figure 21 Industrial sector energy consumption and fuel breakdown (ktoe), MEMR 2023 [32]

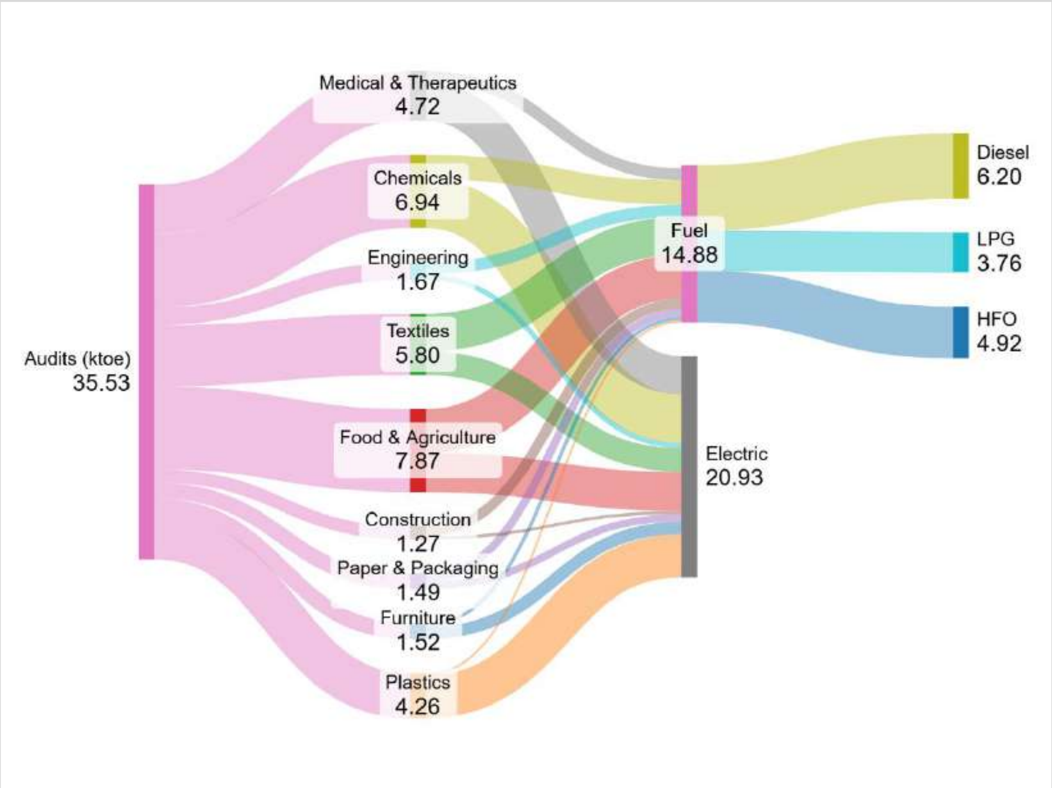


Figure 22 Audited consumption divided by electrical and fuel usage (ktoe)

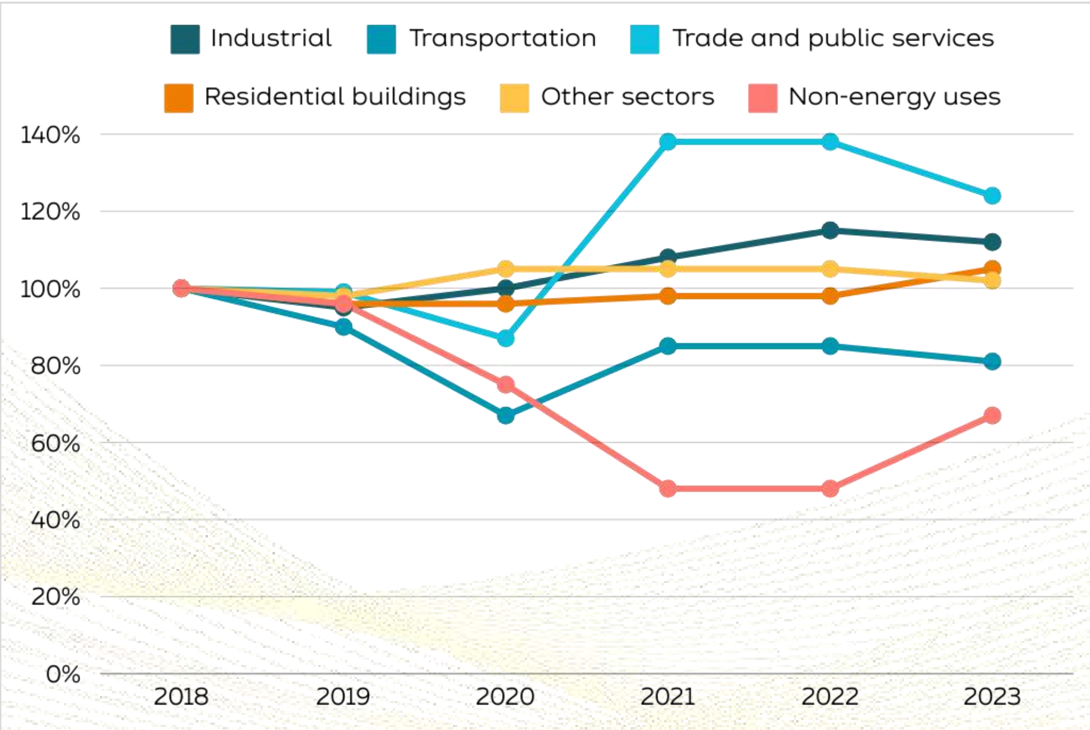


Figure 23 Industrial sector fuel consumption % changes by fuel-type 2018 - 2023, MEMR

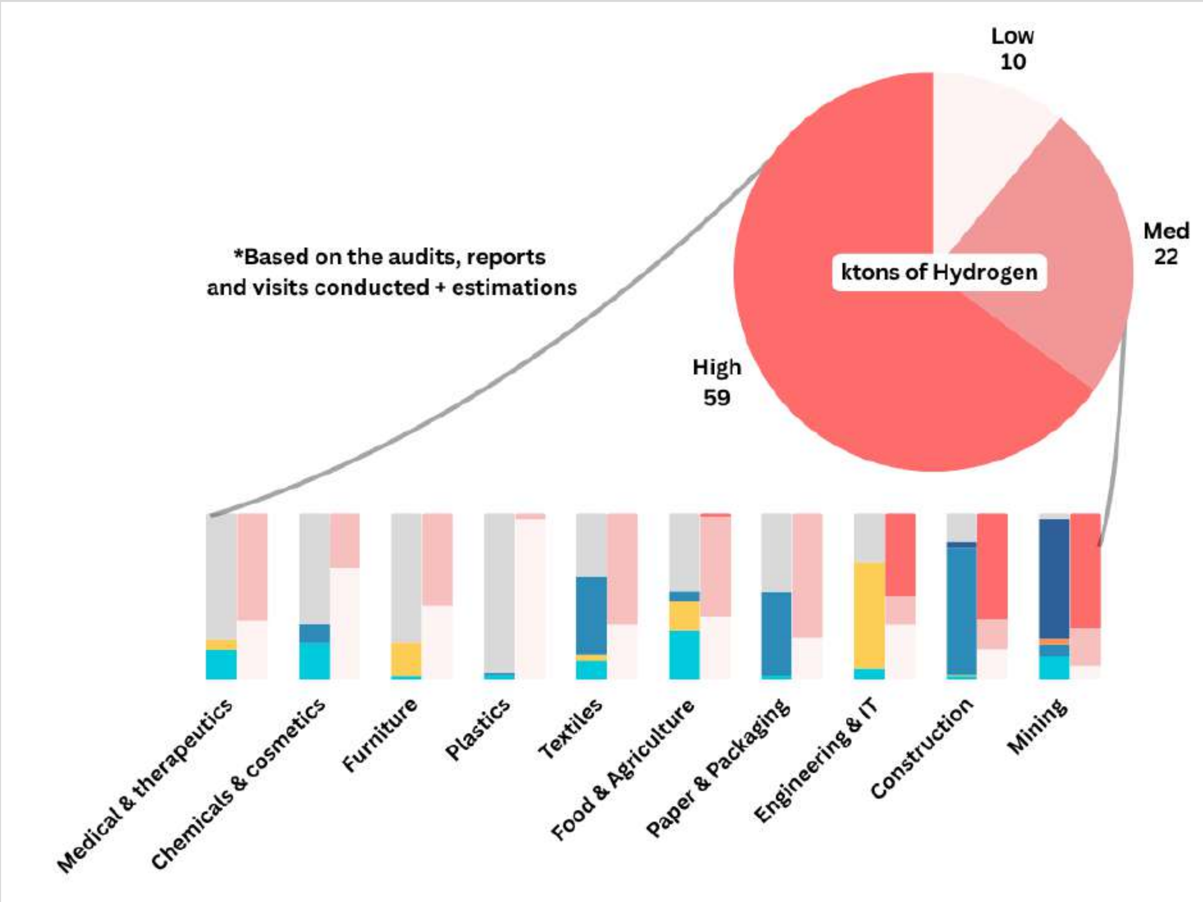


Figure 24 The potential hydrogen (ktons) from the audited and analyzed energy for high, medium and low temperatures

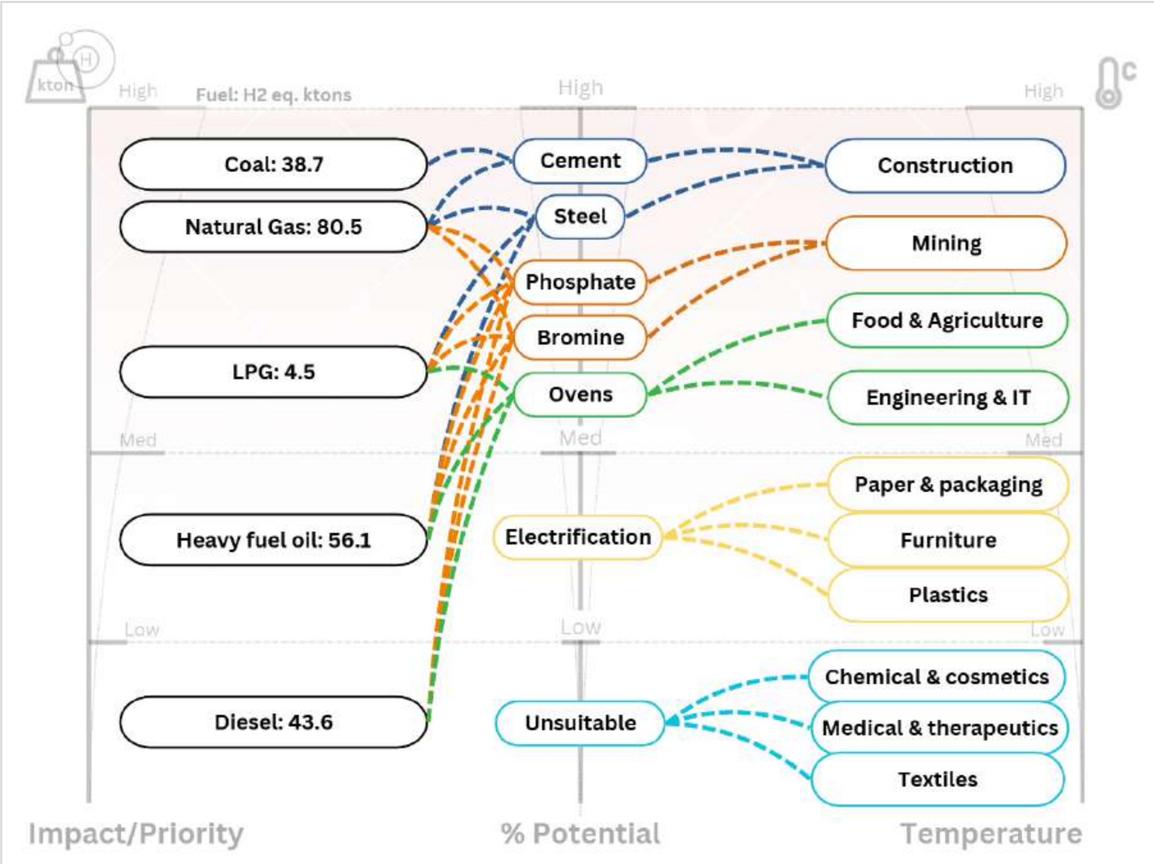


Figure 25 Processes temperatures by sector and path to hydrogen and impact potential from adoption in ktons hydrogen (223.4 ktons total)

	Natural Gas	HFO	Diesel	Coal	LPG	Electricity
Consumption: ktoe	230.8	160.7	124.9	110.9	13	408
Consumption: TWh	2.68	1.87	1.45	1.29	0.15	4.75
H2 equivalent: ktonnes	80.5	56.1	43.6	38.7	4.5	142.4
H2 equivalent: MCM*	14.1	9.8	7.6	6.8	0.8	25

Study coverage by energy consumption	46%
Temperature range reporting	60%

	Low	Medium	High	
H2 equivalent: ktonnes	10	21.9	59	Total by study coverage
H2 equivalent: TWh	0.3	0.7	1.96	
H2 equivalent: MCM*	1.8	3.8	10.4	
H2 equivalent: ktonnes	24.5	53.9	145	Total by extrapolation
H2 equivalent: MCM*	4.3	9.5	25.4	

* Assumed volume conversion condition for hydrogen: density of 5.7 kg/m³ at 70 bar, 20°C

Figure 26 Summary of results and hydrogen equivalency by mass and volume

3.6 Market Dynamics and Distribution Channels

International studies on green hydrogen distribution highlight several critical considerations for effective integration into existing energy systems. For example, utilizing the existing natural gas pipeline infrastructure for hydrogen blending requires thorough testing and preparation to address challenges such as pipeline embrittlement. Alternatively, constructing dedicated hydrogen pipelines, either running parallel to existing networks across the country or strategically positioned near major consumers, represents a key strategic option that warrants detailed financial assessment. This approach, inspired by models like Germany's, facilitates emergency supply management by ensuring redundancy and resilience in energy distribution. Additionally, developing a robust ground supply fleet and investing in hydrogen-compatible vehicles and storage networks are essential steps for efficient and reliable logistics.

In the context of Jordan, while a dedicated distribution network for green hydrogen is not yet established, the existing infrastructure for LPG and natural gas offers a strong potential foundation for adaptation. Jordan's energy distribution framework, particularly for Liquefied Petroleum Gas (LPG) and natural gas, is well-structured and supports current logistical and market uptake strategies. These operations are managed by JoPetrol and its subsidiary, the Jordan Liquefied Petroleum Gas Manufacturing and Filling Company, which oversee cylinder distribution from filling stations in Amman, Zarqa, and Irbid. The Jordan Oil Terminals Company (JOTC) complements these efforts by providing critical storage and terminal services, ensuring efficiency across the supply chain. LPG distribution operates through two key channels: refillable cylinders for residential and small commercial users, and bulk deliveries for industrial and commercial consumers. [Confidential] .

For natural gas, the Arab Gas Pipeline, operated by the Jordanian Egyptian Fajr Company, is transporting natural gas between Egypt, Jordan, and Syria to supply industries and power plants. With appropriate modifications, this pipeline could accommodate hydrogen blending, allowing Jordan to integrate green hydrogen into its energy mix and participate in a regional hydrogen market. Similarly, Jordan's LPG bulk distribution network, with its existing tanker-based delivery system, could be adapted for transporting compressed hydrogen.

These established natural gas channels provide Jordan with a practical and cost-effective starting point for developing a sustainable, hydrogen-ready energy strategy that leverages existing infrastructure while preparing for future energy needs. This could also mean that efforts made towards industrial access to natural gas across the country is a potential effort towards facilitating the introduction of green hydrogen supply to the industry.

3.7 Challenges and barriers

Thus far we have identified issues with economic viability, water resource availability and regulatory hurdles and legislative volatility, but we can still determine a timeline if all of that was fixed. In the pursuit of efficiency and economic improvements and incentives, a lot of large-scale industries with large-scale thermal requirements have transitioned or intend to transition to natural gas as their main fuel source. Even if the economics of green hydrogen were to improve beyond that of natural gas and it became available and otherwise favorable it would still need to wait as most natural gas contracts span about 15 years at a time, with clauses that prevent the manufacturer -through penalties– to switch to a different provider. Recouping the investment in installation and connection is also a factor as it is a highly costly investment of at least 400,000 JOD according to the interviews to simply connect the pipeline.

4 Regulatory framework

This chapter provides an overview and analysis of the regulations and legal framework in Jordan directly or indirectly influencing the production, distribution, and consumption of green hydrogen in Jordan. It is organized into sections to provide a comprehensive analysis of the current regulatory landscape:

1 In the first section, an overview of Jordan's energy sector regulatory framework is presented. This section provides an overview of the entities that hold regulatory responsibilities.
2 The second section is on analyzing regulations related to energy, fuels, and gas. It covers relevant laws governing imports, storage, transportation, and distribution, as well as safety regulations. The investigation also explores opportunities for the private sector in this field.
3 The third section analyses the regulatory framework governing renewable energy and water, which are the main elements used for green hydrogen production.
4 The fourth section is a comprehensive assessment and benchmarking of relevant policies and laws. It details current barriers and challenges, along with authoring the party's reflections and recommendations.

4.1 Overview

Jordan's energy sector is governed by a comprehensive regulatory framework that involves multiple stakeholders, primarily the Ministry of Energy and Mineral Resources (MEMR) and the Energy and Minerals Regulatory Commission (EMRC). The following is an overview of the regulatory aspects and the roles of the respective entities:

4.2 Key Parties Involved

4.2.1 Ministry of Energy and Mineral Resources (MEMR)

The MEMR is responsible for formulating "national" energy policies, overseeing their implementation, and coordinating with various stakeholders in the sector. MEMR is paramount in the incentivization process of energy usage, such as in promoting renewable energy projects and ensuring that regulations align with national objectives.

4.2.2 Ministry of Environment

Ministry of Environment regulations affect the potential of the implementation of renewable energy as well as through the Nationally Determined Contribution (NDC), and the Jordanian commitment to reduce greenhouse gases by 31% by the year 2030. The industrial sector is amongst the main targets to affect the changes required to reach this goal. The sector – by processes - accounts for about 10% of emissions, with a further 6.1% through its energy usage as can be seen in Figure 27 [33], [34].

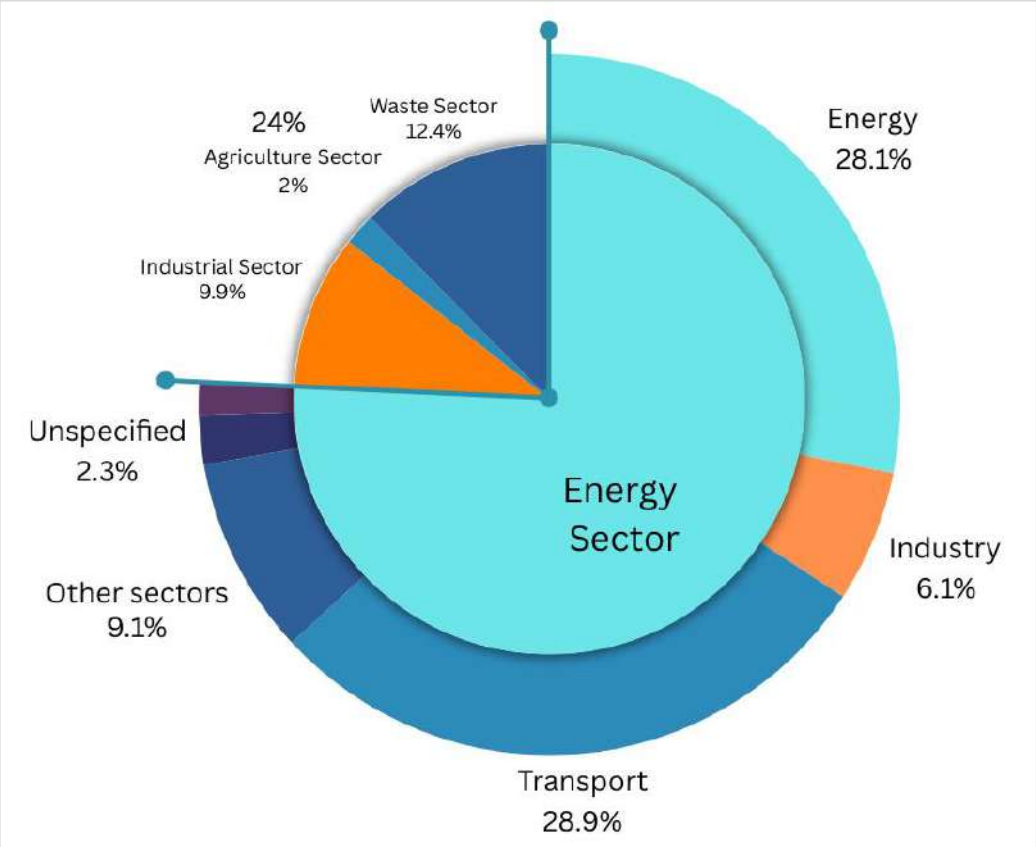


Figure 27 Jordan's GHG emissions 2017

4.2.3 Energy and Minerals Regulatory Commission (EMRC)

Energy and Minerals Regulatory Commission (EMRC) is a governmental body that possess a legal personality with financial and administrative independence and is considered the legal successor of the Electricity Regulatory Commission (ERC), the Jordan Nuclear Regulatory Commission (JNRC), and the Natural Resources Authority (NRA) in relation to its regulatory tasks according to law No. (17) for the year 2014, regarding the restructuring of institutions and governmental organizations [35].

4.3 List of related regulations

4.3.1 Legislation related to fuel imports

Law No. 11 of 2018 on Petroleum Derivatives outlines regulations and provisions governing the petroleum derivatives sector. It includes legal definitions, the roles and responsibilities of relevant authorities, and stipulates guidelines for licensing, trading, and storage of petroleum products. The law aims to organize and control the petroleum derivatives market, ensuring compliance with safety standards and environmental protections while outlining penalties for violations [36]. This should include and apply to the hydrogen market as a combustible fuel but does not currently. Hydrogen does not fall within the definitions stated for petroleum derivatives or biofuels.

Amended System for Licensing Petroleum Derivatives 2023 outlines revisions to the existing regulations governing activities related to the petroleum derivatives sector in Jordan. It includes updates on licensing requirements, fees, and the duration of permits for various petroleum-related activities such as gas importation, distribution, and storage. The amended system defines specific fees for licensing different operations, such as gas filling stations and transportation by tankers, while also detailing the process for renewing or modifying licenses [37]. This system aims to regulate the sector more effectively and ensure compliance with legal standards. Hydrogen as a combustible fuel would fall under gas related provisions for this section.

Petroleum Derivatives Pricing System (2022) outlines the legal framework for pricing petroleum products in Jordan [38]. It details the process by which prices are determined, considering various market factors, including global oil prices and transportation costs. The document sets guidelines for price adjustments and stipulates the relevant authorities, such as the EMRC, which are responsible for monitoring compliance. It also defines the penalties for any violations of the pricing system, aiming to ensure transparency, fair competition, and stability in the petroleum derivatives market [38]. How this might apply to hydrogen as a combustible fuel should be reviewed by MEMR prior to mass or scaled adoption and promotion.

4.3.2 Legislation related to industrial natural gas

The document outlines the 2022 regulations for obtaining permits and licenses related to the purchase, compression, liquefaction, transportation, storage, distribution, and sale of natural gas in Jordan. It establishes the legal framework governing these activities, detailing the necessary procedures and requirements for compliance under the Petroleum Derivatives Licensing System. The regulations specify the roles of various stakeholders, including the Ministry of Energy and Mineral Resources and other relevant governmental bodies, and clarify key terms related to natural gas activities and operations. Additionally, it includes guidelines for site selection, safety standards, and environmental considerations necessary for operating natural gas facilities [39].

4.3.3 Legislation related to renewable energy and water sector

The new renewable energy system regulations were issued in September 2024, and further updated in December of the same year. It focuses on regulations for connecting renewable energy facilities to the national grid, promoting energy efficiency, and exempting renewable energy systems from certain taxes. It introduces mechanisms for integrating renewable energy sources like solar and wind into the grid, providing detailed guidelines for consumers, producers, and the transmission and distribution operators. Additionally, the document includes provisions for exemptions from customs duties and sales tax for renewable energy equipment, alongside the establishment of a committee to oversee these exemptions. The system aims to streamline renewable energy adoption, with specific regulations on energy storage, system connections, and the financial framework for energy transfer and billing [40].

4.4 Challenges and opportunities

Current regulations in Jordan cover the import, storage, transport, and distribution of natural gas to industrial customers, paving the way for further development to cover the scope of green hydrogen. To facilitate the growth of green hydrogen in Jordan, actionable solutions are needed to address the identified regulatory barriers. Below are concise recommendations to streamline the regulatory landscape:

1. Define Hydrogen in Existing Legislation

Issue: Hydrogen lacks clear recognition in current laws.

Recommendation: Amend key regulations, such as the Petroleum Derivatives Law (2018), to explicitly include hydrogen and develop tailored licensing and compliance guidelines under MEMR and EMRC.

2. Establish Safety and Technical Standards

Issue: No specific hydrogen safety regulations exist.

Recommendation: Adopt international hydrogen safety standards (e.g., ISO) and form a dedicated EMRC unit to oversee safe handling, storage, and transport.

3. Enhance Private Sector Participation

Issue: While a wide range of exemptions and incentives for renewable energy systems such as solar and wind, ambiguity and limited incentives related to green hydrogen specific technologies (e.g. electrolyzer, storage) deter investment.

Recommendation: Simplify licensing for hydrogen projects and expand renewable energy tax exemptions to cover hydrogen technologies and infrastructure.

4. Develop Infrastructure Regulations

Issue: Hydrogen-specific infrastructure lacks regulation.

Recommendation: Introduce policies for pipelines, storage, and refueling stations, and mandate hydrogen-ready components in future gas projects.

5. Align Renewable Energy and Water Policies

Issue: While a national hydrogen committee exists, ensuring clear alignment between renewable energy and water policies remains essential for sustainable hydrogen production.

Recommendation: The national hydrogen committee to develop clear policy frameworks that integrate renewable energy and water strategies, ensuring sustainable water use for electrolysis.

6. Create Transparent Pricing Mechanisms

Issue: No clear hydrogen pricing framework exists.

Recommendation: Establish a pricing system akin to the Petroleum Derivatives Pricing System, with temporary subsidies to stimulate market entry.

7. Launch Pilot Projects and Regulatory Sandboxes

Issue: Limited experience with hydrogen technologies.

Recommendation: Support pilot projects and introduce a regulatory sandbox to test innovative hydrogen solutions.

8. Strengthen Regional and Global Collaboration

Issue: Regulatory efforts lack regional integration.

Recommendation: Align hydrogen standards with neighboring countries and leverage international funding and expertise to advance regulations.

9. Streamline Governance

Issue: While a national hydrogen committee has been established to enhance coordination, ensuring its effective implementation in defining clear roles and responsibilities remains crucial.

Recommendation: Ensure the committee functions as a dedicated coordination body with structured mechanisms to prevent regulatory overlap and enhance governance efficiency in hydrogen development. Additionally, strengthen the committee's role as a single-window platform for investors by facilitating regulatory approvals, providing clear guidelines, and enhancing inter-ministerial coordination.

These recommendations offer a focused strategy to overcome regulatory challenges, foster private sector involvement, and position Jordan as a leader in the green hydrogen economy.

Of the listed element the following should be noted as they occurred as the report was being developed:

5 Techno-Economic Assessment of Green Hydrogen Production

This section provides a comprehensive techno-economic assessment of a green hydrogen production system in Jordan-Aqaba. The purpose of this assessment is to evaluate the feasibility and cost-effectiveness of the system while supporting the study's goal of evaluating the potential of green hydrogen adoption for industrial process heating in Jordan. The possible system configurations, designs, and main components selection such as the PV panels and the electrolyzer, together with the grid integration options have been evaluated. A primary focus of the analysis is to balance system size with cost-effectiveness which is essential to achieve the lowest possible Levelized Cost of Hydrogen (LCOH). This section offers an evidence-based and figures-supported comparison with conventional fuels, providing clear directions for the successful implementation of green hydrogen projects in Jordan.

5.1 System Overview

The suggested green hydrogen production system includes the following components: PV panels as the renewable energy (RE) source, a polymer electrolyte membrane (PEM) Electrolyzer, a reciprocating compressor, and a high-pressure storage tank. The hydrogen generated by the Electrolyzer can either be supplied directly to the end-use point or stored in high-pressure tanks for later use. To ensure a continuous hydrogen supply, the grid acts as a backup source. If the demand for hydrogen is met and surplus electrical power remains, it is fed back into the grid. Conversely, when renewable energy yields are insufficient, the Electrolyzer draws electricity from the grid to maintain production.

The Electrolyzer operates using power from renewable sources and/or the grid to either produce hydrogen or maintain specific temperature and pressure levels during standby mode. Transitions between production and standby states are dictated by the characteristics of PEM as a technology, offering flexibility and responsiveness to fluctuating energy inputs. The proposed operating principle is illustrated in Figure 28.

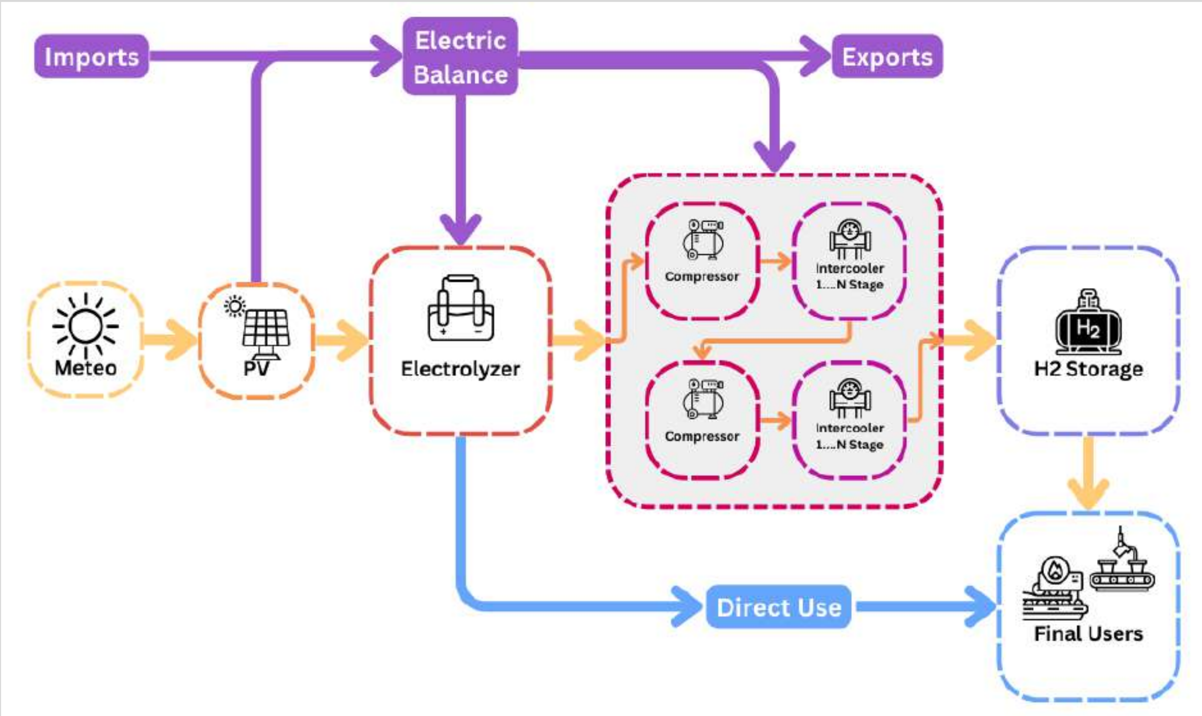


Figure 28 Schematic of the proposed hydrogen production process and supply chain.

5.2 Techno-economic model and LCOH Calculation

In this study, a techno-economic model was developed to evaluate the Levelized Cost of Hydrogen (LCOH) for three electrolyzer sizes to account for small, medium, and large electrolyzer capacities: 1 MW, 10 MW, and 100 MW. The LCOH is determined by summing all relevant cost components. The formula used for the LCOH calculation is based on Fraunhofer (2018) [41] and further refined by Agora (2022) [42] in Eq. (1). The calculation process is illustrated in Figure 29.

$$LCOH = \frac{LHV}{\eta_{sys,LHV}}\left(\left(\frac{\frac{i}{100}\cdot\left(1+\frac{i}{100}\right)^{n}}{\left(1+\frac{i}{100}\right)^{n}-1}+\frac{OPEX}{100}\right)\frac{CAPEX}{\tau}+E\right) \quad (1)$$

Where:

- $LCOH$ is the levelized cost of Hydrogen [JOD/kgH_2]
- LHV is the lower heating value [kWh/kgH_2]
- i is the discount rate [%]
- n is the lifetime [a]
- E is the electricity cost [JOD/kWh]
- $\eta_{sys,LHV}$ is the system efficiency related to the LHV
- τ is the full load hours [hours]

- $OPEX$ is the operational expenditures [% $CAPEX$/a]
- $CAPEX$ is the capital expenditures [€/kW]

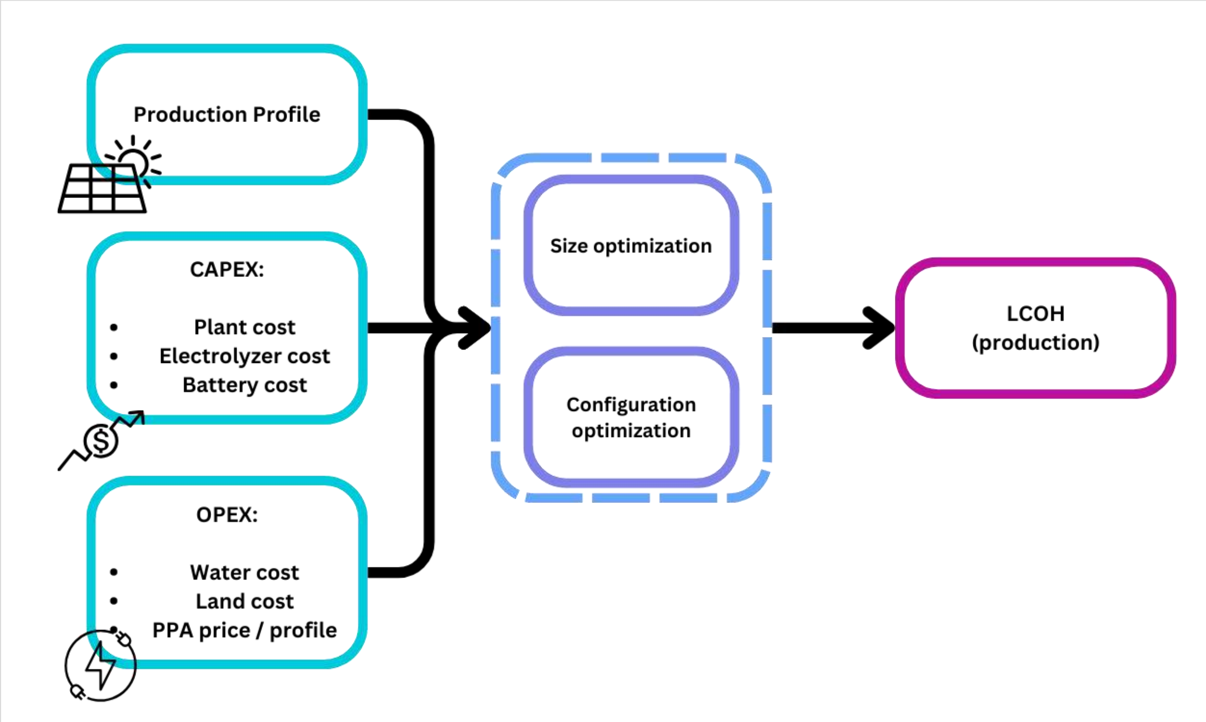


Figure 29 LCOH calculation process.

5.3 Solar System Modeling and Simulation

The utility-scale solar bifacial PV plant with single-axis tracking used to provide renewable electricity for the electrolyzers was simulated using the National Renewable Energy Laboratory (NREL) System Advisor Model (SAM) software [43], version 2023.12.17. The choice of bifacial modules with a single-axis tracking system is based on findings from a previous study, which demonstrated that bifacial systems with single-axis tracking achieve the lowest Levelized Cost of Electricity (LCOE) in the Arabian Desert region [44]. System costs were acquired from the latest global reports, while typical meteorological data for the simulation were obtained from the Photovoltaic Geographical Information System (PVGIS) database [45]. PVGIS is a free web application that provides free access to global databases of meteorological data which are based on satellite imaging and meteorological models covering various locations and timeframes. The simulation was carried out to analyze the techno-economic performance of the PV plants under the climatic conditions of Aqaba city. In the following sections, details about each step in this study are presented.

5.3.1 Meteorological Data

The development of green hydrogen projects in Jordan is mainly planned in the Aqaba region at the Red Sea, to be supplied by desalinated water from the Red Sea with minimal pumping energy consumption. Additionally, Aqaba benefits from high solar radiation, as illustrated by the Global Horizontal Irradiance (GHI) map of Jordan. The maximum GHI in Aqaba reaches **230 kWh/m²** in July making it an ideal location for this study. The latitude, longitude, elevation, daily average GHI, and average temperature for Aqaba are presented in Table 2. The monthly GHI and the minimum and maximum temperatures for Aqaba are presented in Figure 31. The climate in Aqaba is characterized by intense solar radiation, with the highest levels occurring between June and August. It is a hot region, with temperatures exceeding 40°C from May to September. Even during the winter months, maximum temperatures remain relatively warm, consistently above 20-25°C.

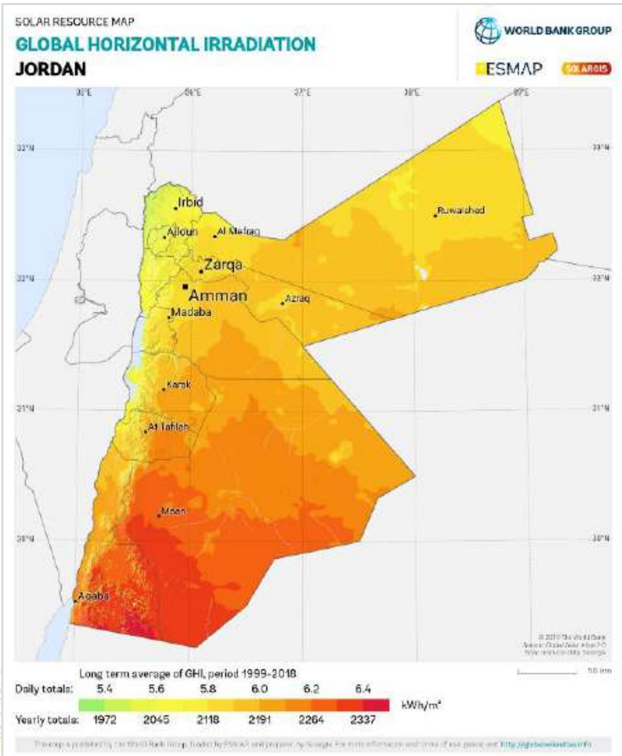


Figure 30 Jordan's GHI map [46].

Table 3 LCOH analyses site meteorological data

City	Latitude (°N)	Longitude (°E)	Elevation (m)	GHI (kWh/m²/day)	Average Temperature (°C)

Aqaba	**29.55**	**35**	**12**	**5.56**	**24.7**

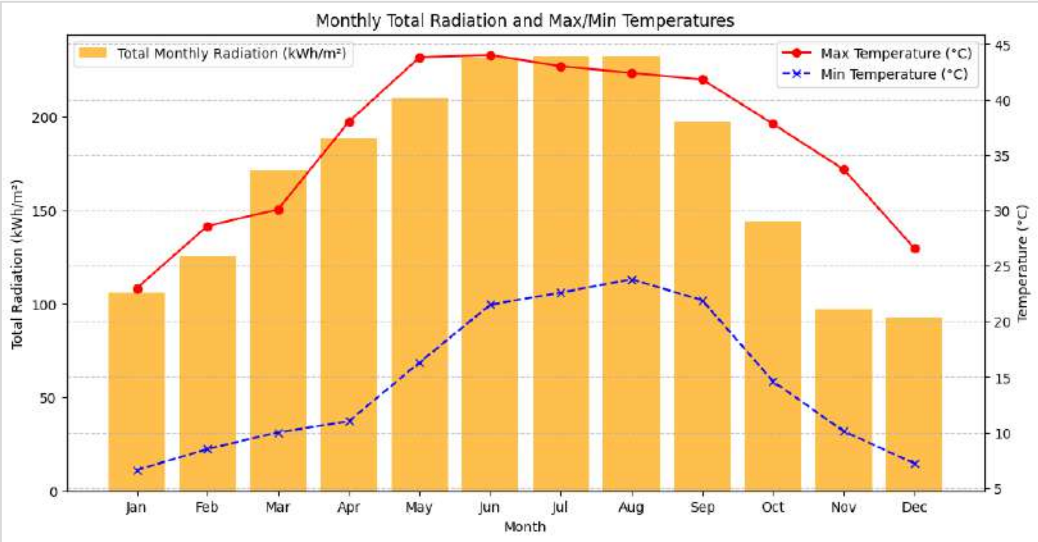


Figure 31 Monthly GHI and Max/Min temperatures in Aqaba.

5.3.2 Techno-economic model of the solar PV system

The PV plant design is based on real utility-scale project designs [47]. Both the PV panels and the inverter used in the design are proven technologies, already deployed in utility-scale PV projects under similar climates. The PV panels are bifacial with a peak power of 665 W, an efficiency of 21.4%, and a bifacilaity factor of 0.7 [48]. The inverters used in the design have a capacity of 250 kW each [49]. Table 4**Error! Reference source not found.** presents the main technical parameters used in the System Advisor Model (SAM). The PV system's size was optimized to achieve the lowest LCOE, maximize Full Load Hours (FLH) for the electrolyzer, and satisfy the monthly matching requirements of renewable energy production with hydrogen production. This alignment adheres to the European Union's transitional measures to facilitate the growth of green hydrogen projects.

Table 4 Main technical parameters used in the SAM model.

Description	Characteristics	Value
PV Modules	**Panel model**	**Trina Solar: TSM-DEG21C.20**
	Maximum power (Pmp)	**665 W**
	Maximum power voltage (Vmp)	**38.3 V**
	Maximum power current (Imp)	**17.39 A**
	Open circuit voltage (Voc)	**46.1 V**
	Short circuit current (Isc)	**18.50 A**
	Module efficiency (η)	**21.40%**

Inverter	**Inverter model**	**Sungrow Power Supply Co., Ltd.: SG250HX**
	Maximum AC power	**250 kW**
	Maximum DC voltage	**1500 V**
	Number of inverters	**4**
System Design	**Modules per string in array**	**27**
	Strings in parallel array	**72**
	Modules in subarray	**1,944**

5.3.3 Economic parameters for LCOE calculation

The LCOE is used to compare the economic viability of the PV plants under different climatic conditions. The LCOE is widely used to compare the cost of electricity production from different technologies, or to compare the cost of electricity production using the same technology but in different locations. It is the present or current value of the project's cost in relation to the electricity produced by the plant over its entire lifetime expressed in JOD per kWh. Table 5 outlines the economic parameters used to calculate the LCOE and provides inputs needed for the comprehensive assessment of PV plant costs. This method allows for consistent and comparable analysis across different locations and technologies, such as:

- Different energy technologies (e.g., solar vs. wind or fossil fuels).
- The same technology is deployed in different locations with varied conditions.

Table 5 Economic parameters used to calculate the LCOE.

Parameter	Value
Analysis Period	20 years
Inflation Rate	2.5% per year
Internal Rate of Return (Nominal)	13% per year
Project Term Debt	60% of capital cost
Nominal Debt Interest Rate	7% per year
Effective Tax Rate	28%
Nominal Construction Interest Rate	3.5% per year
Capital Recovery Factor (CRF)	0.084
Project Financing Factor (PFF)	1.075
Construction Financing Factor (CFF)	1.012
Variable Operating Cost (VOC)	JOD 0.00/kWh
Fixed Charge Rate (FCR)	0.0903

The Fixed Charge Rate (FCR) is essential for annualizing the Total Capital Cost (TCC) over the plant's lifetime. It combines the Capital Recovery Factor (CRF) and

Project Financing Factor (PFF). The relationship is expressed in Eq. (2) and the LCOE calculation in SAM is simplified as shown in Eq. (3) as follows:

$$FCR = CRF \times PFF \quad (2)$$

$$LCOE = \frac{(FCR \ \times TCC + FOC)}{AEP} + VOC \quad (3)$$

Where FOC is the fixed annual operating cost and AEP is the annual electricity production in kWh. The utility-scale PV installed costs for the selected deserts in this study were obtained from reports by the International Renewable Energy Agency (IRENA) [50] and the NREL [51]. According to these reports, in 2022, the average total installed costs of utility-scale solar PV ranged from USD 640/kW in India to USD 1905/kW in Japan. The weighted average cost for utility-scale systems installed worldwide in 2022 was USD 876/kW. These costs vary by country due to differences in hardware costs, installation costs, and other costs related to financing, permitting, and incentives. Based on the market average and reports by IRENA and NREL, the selected CAPEX of the system is 630 JOD/kWac while the Operation and Maintenance (O&M) costs are 10 JOD/kWac.

5.4 Electrolyzer

The electrolyzer is a critical component of the hydrogen production system. It consists of the stack, where the water-splitting reaction takes place, and the balance of system (BOS), which includes elements such as the power supply, water supply and purification, compression, and electricity and hydrogen buffers. Both the stack and BOS components contribute significantly to the overall cost, as they share similar cost proportions.

A PEM Electrolyzer was chosen to decompose pure water into hydrogen and oxygen. The characteristics of PEM electrolyzer technology versus other technologies are further shown in Table 6. As clearly stated in [52], PEM solution ensures higher efficiency, longer life span, and greater flexibility than alkaline technology. Additionally, it operates effectively over a broader range of off-design loads, and its ramp speed is significantly improved [53]. PEM electrolysis is currently the best option available, offering the advantage of quickly reacting to the fluctuations typical of renewable power generation.

	Alkaline	AEM	PEM	SOEC
Development Status	Maturer	R&D	Commercialized	R&D
Operating Temperature (°C)	70 - 90	40 - 60	50 - 80	700 - 850
Cell Pressure (bar)	<30	<35	<70	1 bar
Efficiency (%)	50 - 78	57 - 59	50 - 83	89 (laboratory)
Efficiency (kWh/kg H2)	50 - 78	57 - 69	50 - 83	40 - 55
Stack Lifetime (hrs)	60,000	>30,000	50,000 - 80,000	20,000
Critical Raw Materials	Pt, Co	-	Pt, Ir, Ru	Gd, Zr, La, Ce, Y

Table 6 Overview of water electrolysis technologies for green hydrogen production [20]

Electrolyzer efficiency (η_{EL}) was defined as hydrogen energy based on its High Heating Value (HHV) divided by electricity consumption. The part-load behavior was assessed through an η_{EL} curve as a function of load, shown in Figure 32, as suggested by Mancera et al. [54]. Based on electrolyzer efficiency values presented in Table 6 and Figure 32, an average operating efficiency of 70% was found on an annual basis.

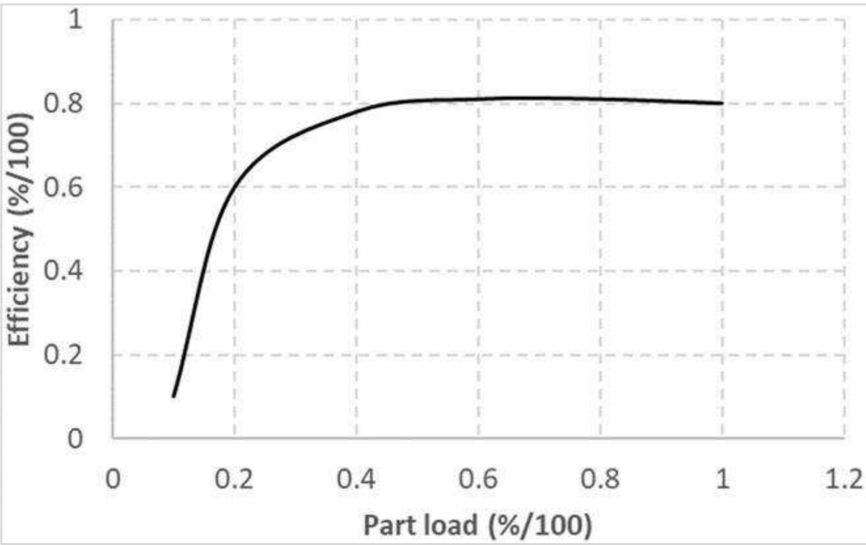


Figure 32 Electrolyzer efficiency at part-load (η_{EL}) [55].

The cost of deploying electrolyzers varies with capacity. The study assumes a CAPEX of 1000 JOD/kW for a 1 MW electrolyzer [[56] and [57], while the annual maintenance costs – in JOD/year - were calculated as 5% of the CAPEX. The CAPEX was reduced to 724.44 JOD/kW for a 10 MW system and 524.81 JOD/kW for a 100 MW installation. This cost reduction is based on a CAPEX scaling factor presented in Eq. (4) which is taken from [56] that is derived from values originally presented in [58], [59], [60]. The share of CAPEX as a function of electrolyzer size is illustrated in Figure 33.

$$CAPEX\ Scaling\ Factor = X^{-0.1976} \tag{4}$$

Where X stands for the electrical rated power of the electrolyzer system (1 ≤ X ≤ 100 MW) in the unit MW. With this scaling factor, CAPEX or the LCOH can be compared for electrolyzers of different capacities.

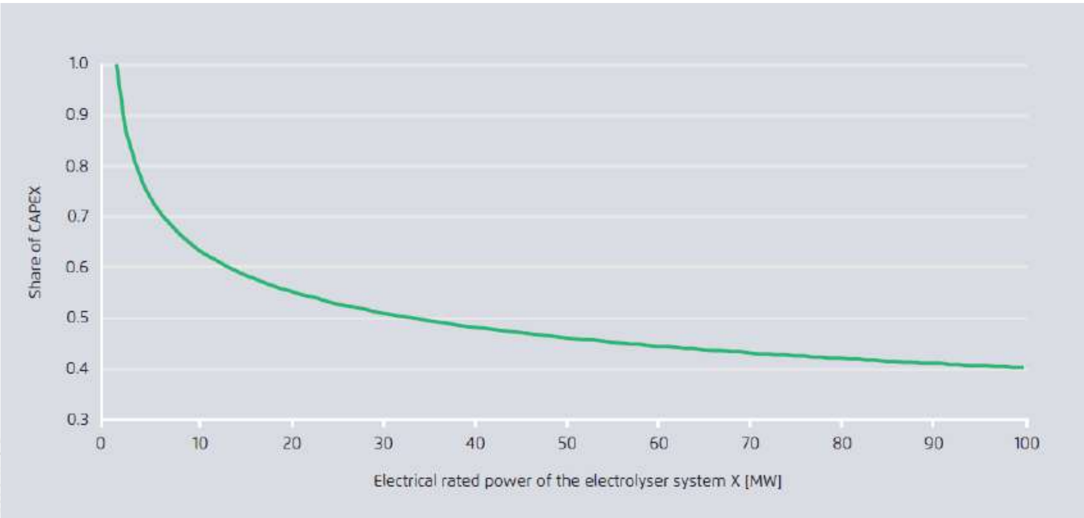


Figure 33 Share of CAPEX (%) as a function of the rated power capacity of the electrolyzer system (MW) [56].

5.5 Results

5.5.1 Baseline scenario

The analysis in this scenario considers a net metering integration scheme for renewable energy, as was applicable in Jordan at the beginning of this study. Additionally, compliance with Article 11 of the Commission Delegated Regulation (EU) 2023/1184 is ensured. This regulation requires hydrogen producers to demonstrate that renewable hydrogen is produced during periods when renewable electricity is available. Specifically, the production of renewable hydrogen must occur within the same calendar month as the generation of the renewable electricity [61].

Thus, the yellow bars in Figure 34 represent the constant energy load of the 1 MW electrolyzer, which requires around 700 MWh each month for full load operation. Four PV system sizes — 1 MW, 2 MW, 3 MW, and 4 MW — are analyzed to determine how well they cover this demand throughout the year. The main constraint that has been ensured in this analysis is to match the renewable power generation with its associated renewable hydrogen production on a monthly basis.

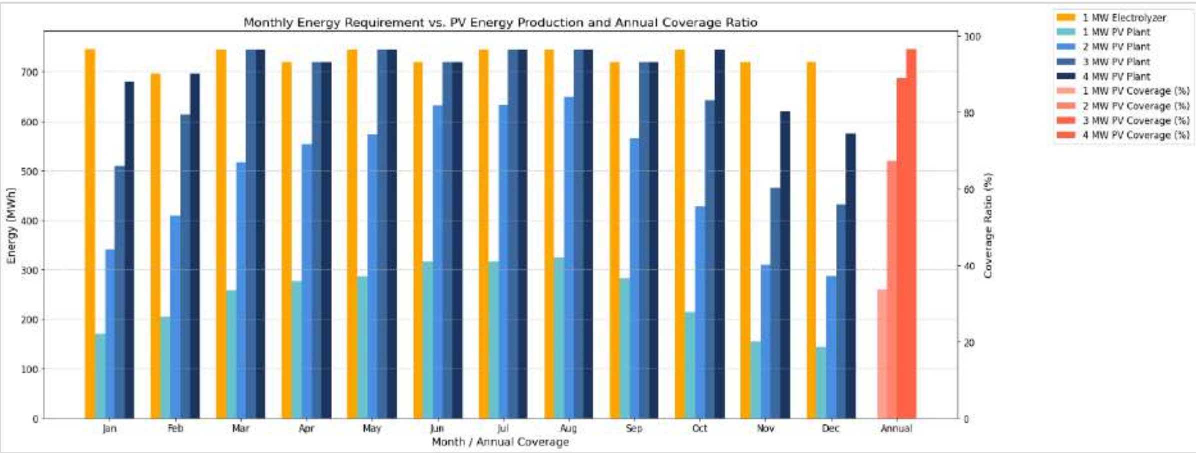


Figure 34 Monthly electrolyzer energy requirement (1MW electrolyzer) vs. monthly PV system energy generation (1-4 MW).

The 1 MW PV plant falls significantly short of the requirement, achieving just about 30% in annual coverage. In comparison, the 2 MW PV system nearly doubles this performance, with about 60% of the electrolyzer's annual energy demand covered. Since the analysis runs on a monthly basis, the performance of the 3 MW and 4 MW systems during the summer months is identical, as both exceeds the electrolyzer load.

The main distinction between the 3 MW and 4 MW systems becomes evident in the winter months when solar irradiation is at its lowest. The 4 MW system provides better load coverage under these conditions. However, increasing the PV system size to improve winter performance comes with a trade-off. A larger plant raises the CAPEX, which together with unused excess energy during the summer months increases the LCOE and ultimately results in a higher LCOH. Balancing system size with cost-effectiveness is essential to maintaining an economically viable hydrogen production process.

Figure 35 and Figure 36 show the hourly energy production over four selected days in summer (June) and winter (January). Naturally, it depends on the selected geographical location and its meteorological conditions, such as the level of solar irradiation. At the same time, the technology chosen for renewable resources will also affect this critical parameter. Therefore, the more reliable the production curve information is, the more accurate it will be, leading to a more precise calculation of the LCOH, as it will tell us how much renewable energy is fed into the system.

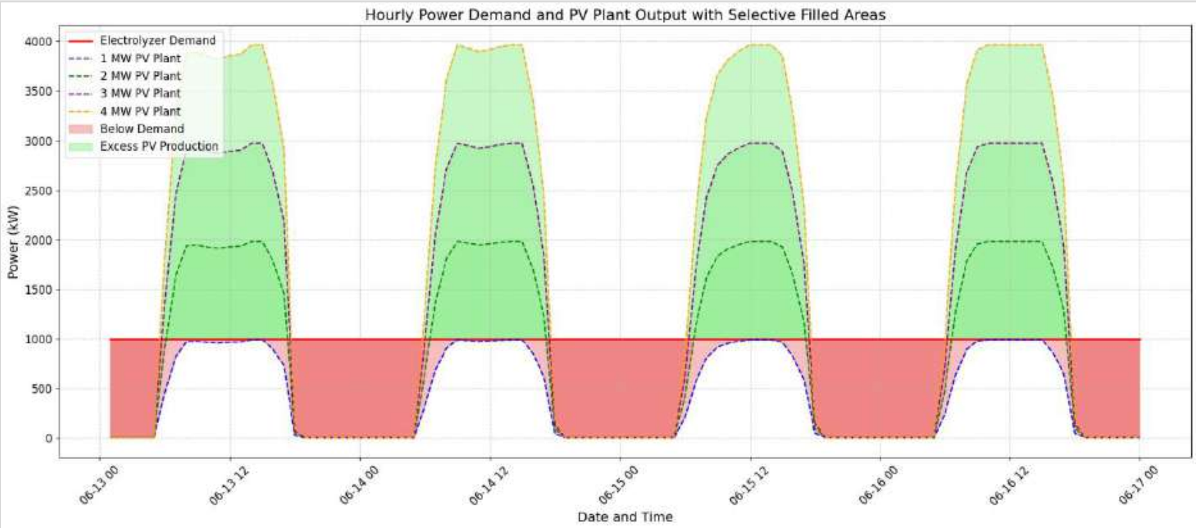


Figure 35 Hourly PV energy production vs. electrolyzer demand over four selected summer days (June).

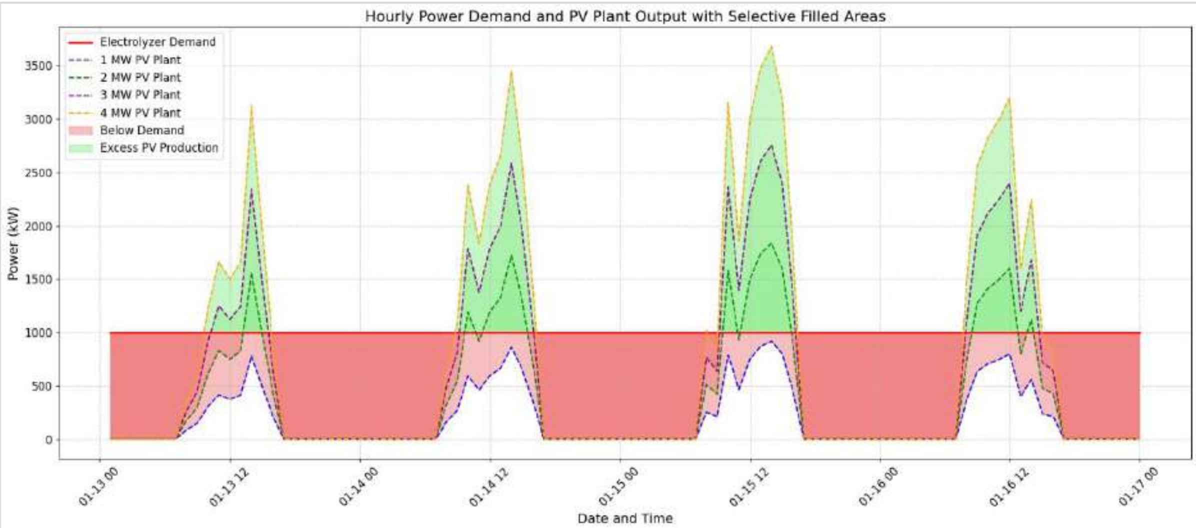


Figure 36 Hourly PV energy production vs. electrolyzer demand over four selected winter days (January).

The electrolyzer operates continuously, maintaining a constant load, represented by the red line in Figure 35 and Figure 36, throughout the 24-hour cycle. However, the PV systems only generate energy during the day, leading to a dependency on grid power during nighttime and periods of low solar output. The red-shaded areas show the periods when the electrolyzer demand exceeds the PV output, indicating situations where energy must be supplied from the grid to maintain uninterrupted operation if the monthly exported energy could cover this demand, or turning off the electrolyzer.

The green-shaded areas represent surplus PV production, where the PV output exceeds the electrolyzer's demand during peak sunlight hours. This excess energy helps offset grid consumption by compensating for the energy shortfall at other times, reducing the overall reliance on grid electricity. Maximizing this excess production while minimizing curtailment is essential for decreasing both the LCOE and the LCOH.

In summer, the 2, 3, and 4 MW PV plants produce substantial surplus energy, contributing more effectively towards offsetting the energy taken from the grid. In contrast, the 1 MW PV plant generates less surplus and shows increased dependence on the grid, as it is unable to meet the intra-day electrolyzer demand even when the sun is up. In winter, the total energy production from all PV systems decreases, resulting in larger red areas as shown in Figure 35 and Figure 36, indicating higher grid consumption. Here, even the 2 MW system produces less excess energy in winter, being unable to meet the electrolyzer load during the day. These surplus and shortfall values are eventually summed up every month, previously presented in Figure 34. The overall analysis shows the importance of balancing system size to maximize PV surplus during the day while minimizing the need for grid energy at night and in low solar conditions.

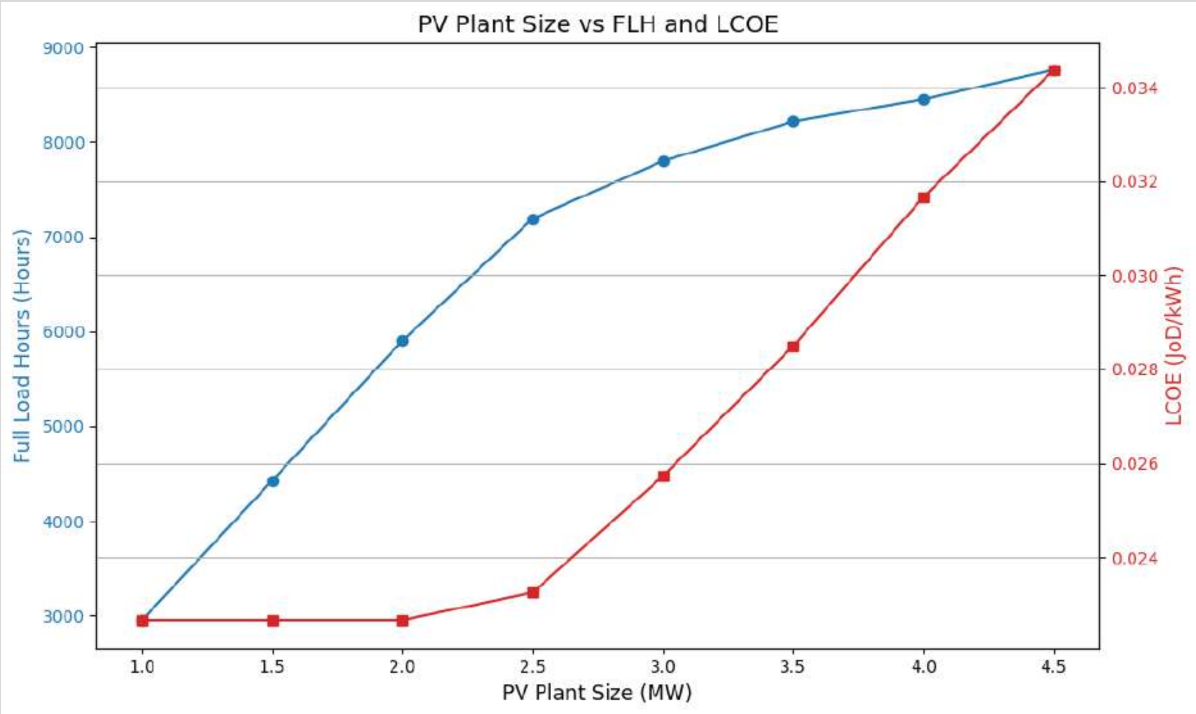


Figure 37 PV plant size vs. FLH and LCOE.

Figure 38 reflects the trade-off observed in the previous monthly analysis between increasing PV plant size and its impact on both LCOE and FLH. As shown, increasing the PV system size improves the FLH, meaning the electrolyzer can operate closer to its full capacity for more hours annually. This aligns with the earlier findings where larger PV plants, particularly 3 MW and 4 MW, were able to generate surplus energy during peak solar hours, reducing grid dependence. However, Figure 38 also illustrates that increasing PV size beyond 2-2.5 MW leads to a noticeable rise in LCOE, driven by higher CAPEX requirements and the more curtailed energy. While a larger PV plant helps reduce grid reliance and enhance hydrogen production efficiency, the increase in CAPEX raises the overall cost of energy production. This trade-off is critical when designing the system to balance the cost-effectiveness of hydrogen production against improved operational performance with higher FLH.

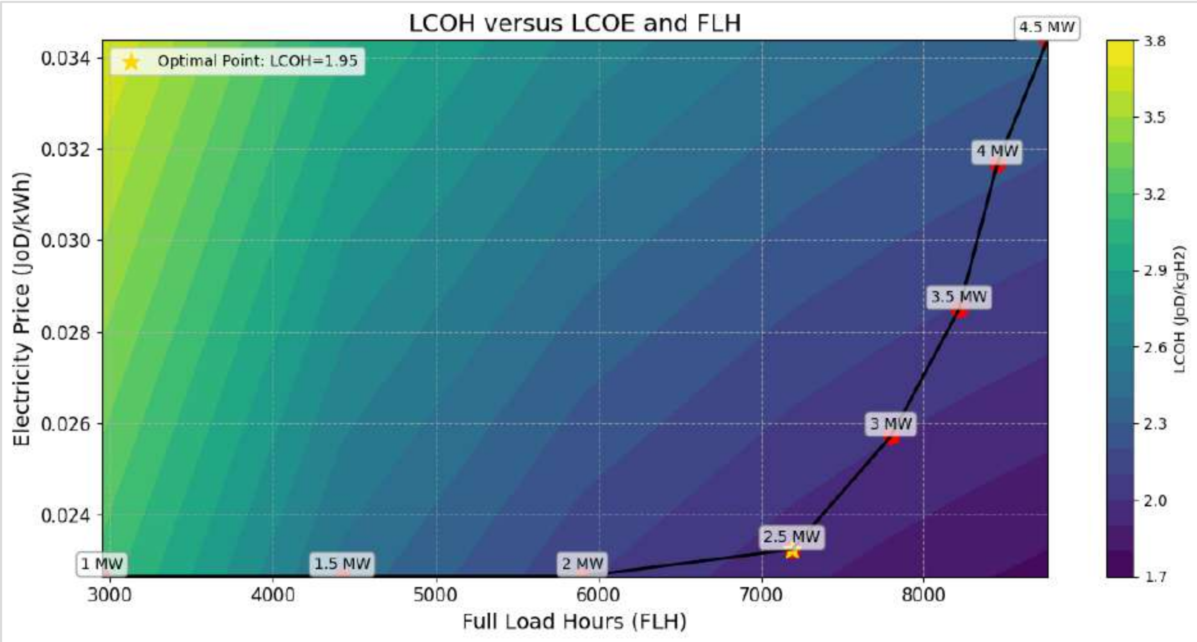


Figure 38 LCOH vs. LCOE and FLH

Figure 38 presents the Levelized Cost of Hydrogen (LCOH) as a function of the Levelized Cost of Energy LCOE (JOD/kWh) and Full Load Hours (FLH); i.e. the higher FLH and lower LCOE would result in lower LCOH as shown in the bottom right corner of the chart. The different PV plant size scenarios investigated are presented by the red circles with the text labels indicating the PV plant size, for example, a plant size of 1 MW would run the electrolyzer for 3000 FLH, produce electricity at a cost of 0.023 JOD/kWh, and the produce hydrogen for 3.3 JOD/kgH2 as shown in the bottom left of the chart. Different points along the black line correspond to various PV plant sizes (e.g., 1 MW, 2.5 MW, 4 MW). The star marks the point of lowest LCOH, which is 1.95 JOD/kgH_2 , achieved at a 2.5 MW PV plant size with specific electricity pricing and operational conditions. Beyond this point, further increases in PV capacity yield diminishing returns, with the LCOH rising due to higher electricity costs despite the longer operational hours. This reinforces the need to ensure that FLH is maximized without driving LCOE — and consequently LCOH — too high.

The techno-economic assessment in this section provides a systematic, generalizable approach to optimizing green hydrogen (GH_2) production by balancing component selection, system size, and integration strategies. It concludes that the lowest Levelized Cost of Hydrogen (LCOH) is achieved by optimizing PV plant size, electrolyzer capacity, and grid integration. Through data-driven modeling and scenario analysis, the study offers actionable insights and a replicable framework for cost-effective, scalable green hydrogen deployment in industrial applications.

5.5.2 Expanded Scenarios Including Policy and Technology Changes

To provide stakeholders with a more comprehensive view of green hydrogen's future trajectory in Jordan, it is essential to incorporate expanded scenarios that reflect potential policy developments and technological advancements. This approach aligns with the sensitivity analysis conducted for the Levelized Cost of Hydrogen (LCOH), which examines the impact of variations in critical parameters such as electrolyzer cost, efficiency, and the policy related to the connection of solar systems that directly affects the Levelized Cost of Electricity (LCOE). The analysis, as shown in Figure 39, highlights the pivotal role of energy costs and technological improvements in shaping the economics of green hydrogen. For instance, a 40% decrease in the LCOE of PV results in over a 20% reduction in LCOH, underscoring the significant sensitivity of hydrogen production costs to renewable energy prices. Similarly, advancements in electrolyzer technology, such as cost reductions and efficiency gains, demonstrate their influence, albeit less pronounced compared to energy costs. These findings emphasize the necessity of exploring scenarios that incorporate dynamic changes in policies and technologies to better understand and plan for the evolving landscape of green hydrogen in Jordan. The impact of policy development related to the possible connection scheme of PV system to power the electrolyzer plant is further explored in the next sections.

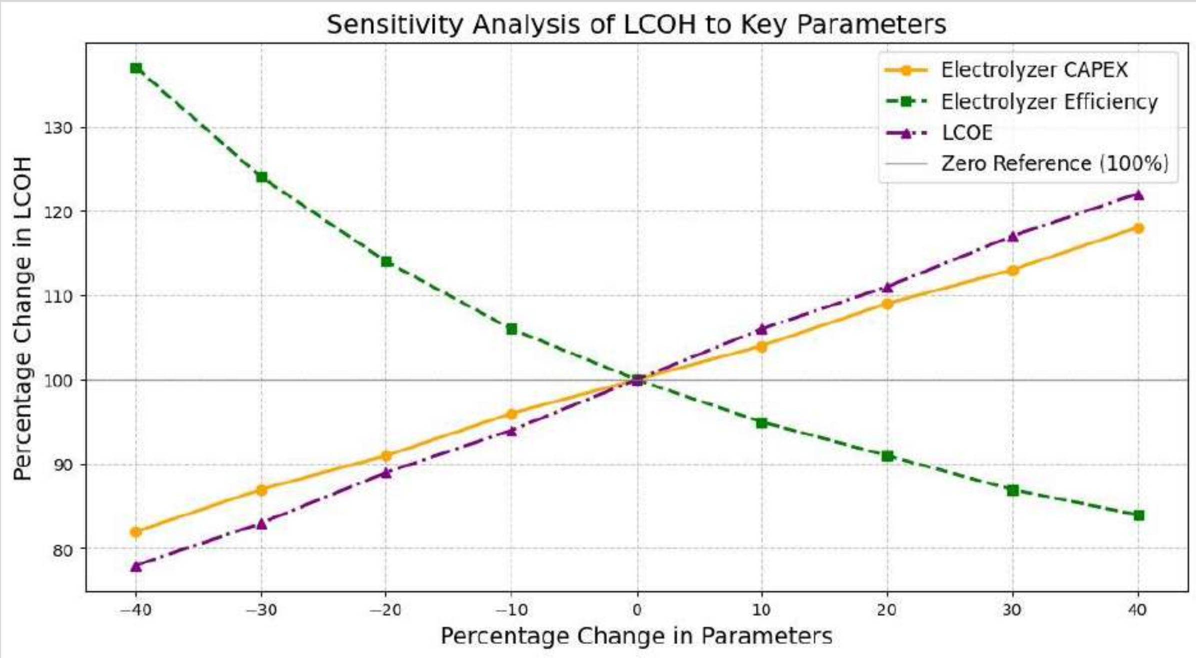


Figure 39 Sensitivity analysis of LCOH to key parameters, showing the percentage change in LCOH with respect to variations in electrolyzer CAPEX, electrolyzer efficiency, and LCOE.

The previous analysis identified the optimal LCOH for the 1 MW electrolyzer at 1.95 JOD/kgH_2 , balancing system costs and operational efficiency. However, increasing the size of the electrolyzer further reduces the LCOH due to economies of scale, improving both capital and operational efficiency. For a 10 MW electrolyzer, the optimal LCOH decreases to 1.75 JOD/kgH_2 , and for a 100 MW electrolyzer, it drops further to 1.55 JOD/kgH_2 . These reductions highlight the cost benefits of scaling up the electrolyzer capacity, though larger systems may require higher initial CAPEX and more comprehensive integration with renewable energy sources to maintain efficiency and cost-effectiveness.

5.5.3 Expanded Scenarios considering different grid integration policy

Previous analyses ensured the monthly matching required for renewable power generation and their associated renewable hydrogen production. In other words, renewable hydrogen producers can run their electrolyzers at any hour that the total amount of renewable electricity consumed corresponds to the total amount of renewable hydrogen produced within that calendar month of the year. This will allow renewable hydrogen producers to deliver a constant stream of renewable hydrogen to their clients, especially in those cases where no hydrogen infrastructure or storage options are available yet.

It is important to mention that during the preparation of this report, a new legislative framework was approved in Jordan by the Ministry of Energy and Mineral Resources (MEMR) on September 2, 2024. This framework replaces the previously approved net metering mechanisms with alternatives such as net billing and zero-export systems, emphasizing self-consumption and grid stability. Under the new framework, users are responsible for connection costs, and the capacity of renewable energy systems is limited to the user's consumption levels [62].

- For large industries, electricity produced by PV systems can be sold to the grid at 0.04 JOD/kWh, while purchasing electricity from the grid costs 0.128 JOD/kWh.
- For medium industries, electricity produced by PV systems can also be sold to the grid at 0.04 JOD/kWh, while purchasing electricity from the grid costs 0.068 JOD/kWh.

Thus, two new scenarios considering large and medium industries have been further investigated and optimized similar to the base scenario. Figure 40 presents the LCOE, FLH, and LCOH for the net metering scenario (in red line), the renewable energy system for large industry connection scheme (in green line), and the renewable energy system for medium industry connection scheme (in blue line) for different system capacity sizes.

The implementation of these connection schemes resulted in an increase of the LCOE significantly compared to the net metering, and thus the optimal LCOH obtained for net metering, medium industry, and large industry are 1.95 JOD/kgH_2, 2.5 JOD/kgH_2, and 3.09 JOD/kgH_2 respectively. These results explicitly highlight the importance of the regulatory framework to integrate newly added renewable energy sources for hydrogen production. Such a framework is essential to avoid additional costs that could inflate the levelized cost of energy (LCOE) and hinder efforts to promote green hydrogen development in Jordan.

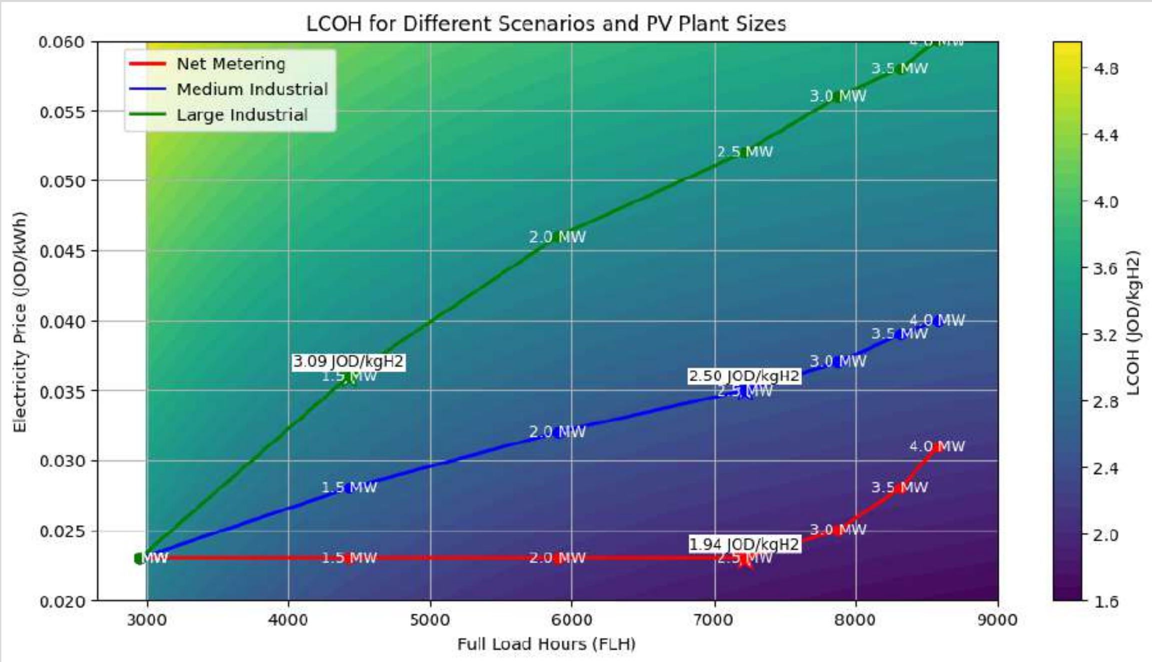


Figure 40 LCOH for different scenarios and PV plant sizes

The unit cost of fuel in terms of JOD/kWh was calculated for the fuels used in the industry, i.e., LPG, natural gas, diesel, and HFO for the last four years. The prices are plotted together with the hydrogen estimate cost in Figure 41. This figure shows the higher cost of hydrogen compared to other fuels, which could be 3-4 times more than natural gas.

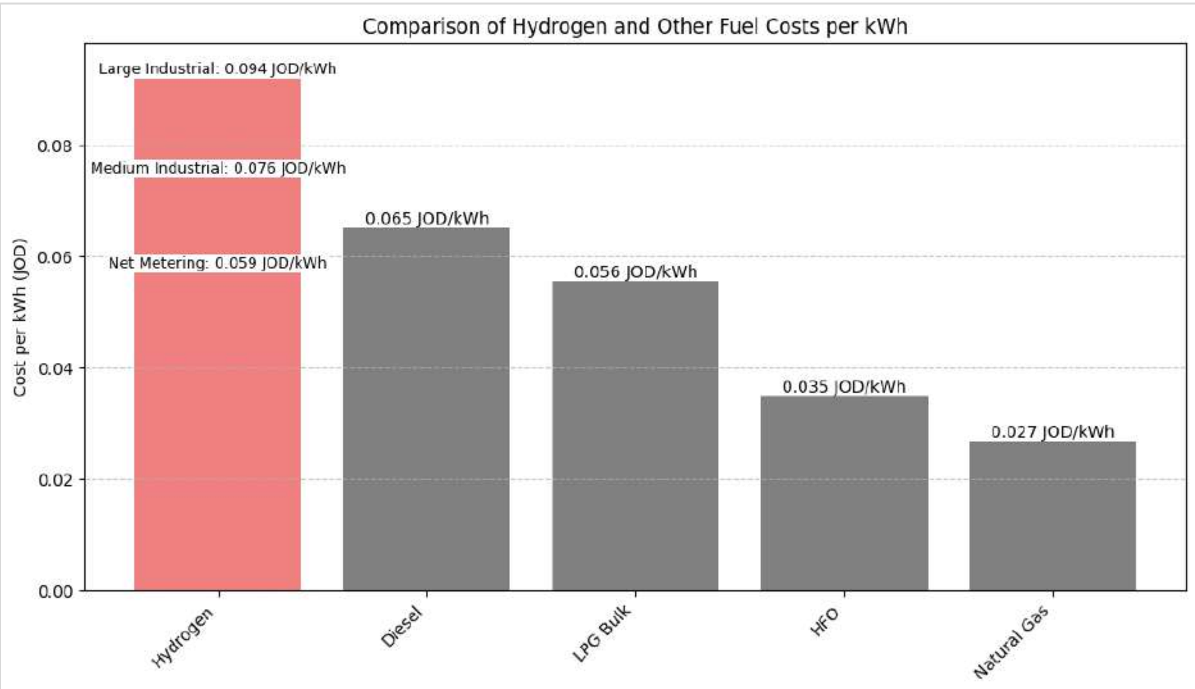


Figure 41 Comparison of hydrogen and other fuel costs per kWh

6 Conclusions and recommendations

Jordan's industrial sector is an essential component of the national economy, contributing around 25% of GDP, employing 21% of the workforce, and generating $9 billion in annual exports. However, it is responsible for 7.6% of the country’s total emissions, largely due to the reliance on fossil fuels for industrial heat. The sector encounters multiple challenges, such as high energy costs, dependence on energy imports, and competition from regional markets.

The industrial sector's energy consumption is divided between fuels (61%) — mainly used for heat — and electricity (39%), previously shown in Figure 21. Recent trends show a shift towards natural gas to reduce costs, although the high initial cost for infrastructure and long-term contracts (typically 15 years) complicate flexibility for the given industries. Between 2018 and 2023, fuel consumption fluctuated in response to market conditions and policy changes.

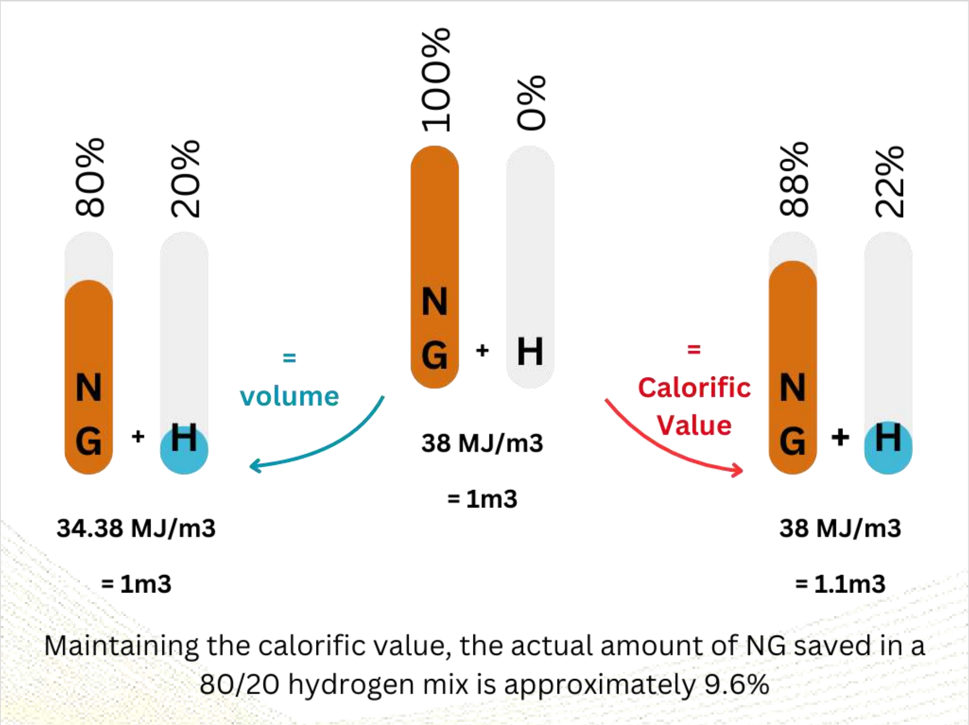


Figure 42 Mixing natural gas and hydrogen by volume vs mass

As previously mentioned, mixing hydrogen with natural gas requires adjustment to the quantity of the fuel being used and byproducts that may be included in the final product (such as in the case of ash incorporation in the cement manufacturing process). Maintaining the calorific value and mix adjustments are summarized in Figure 42. Figure 43 and Figure 44 show how converting the entire combustible fuel portfolio, analyzed and totally reported for the country respectively, would be accounted for if converted to hydrogen instead. These estimations focus purely on energy requirements and do not account for associated costs, efficiency factors, or conversion losses during production and combustion. They serve as a baseline for understanding the energy scale required for a transition to hydrogen.

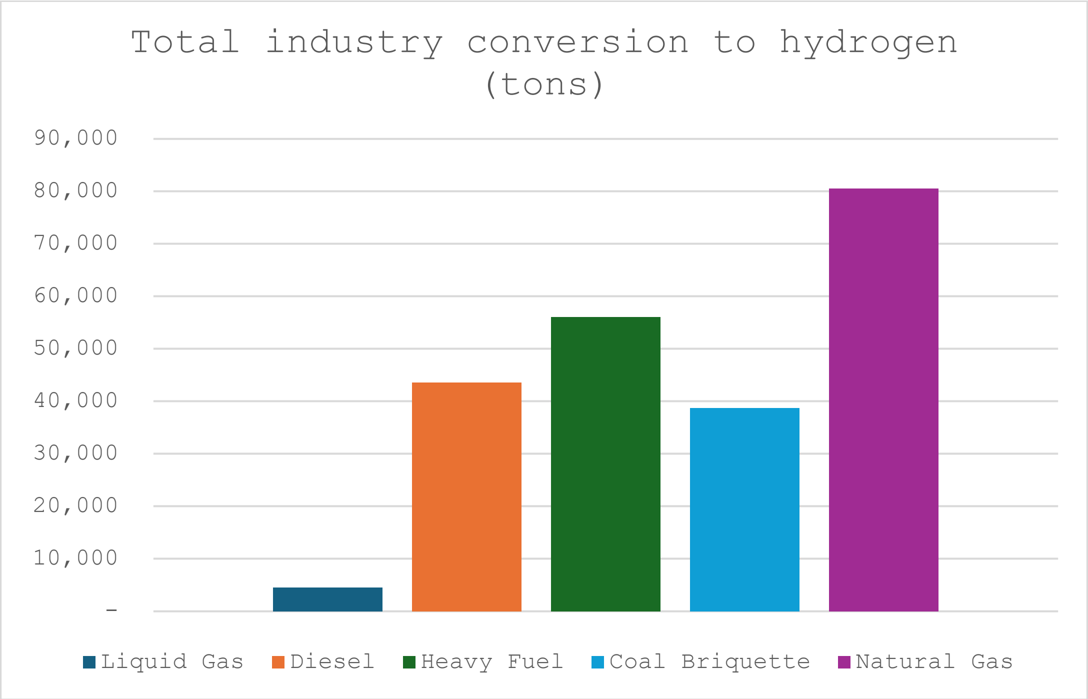


Figure 43 Total industry conversion to hydrogen (tons)

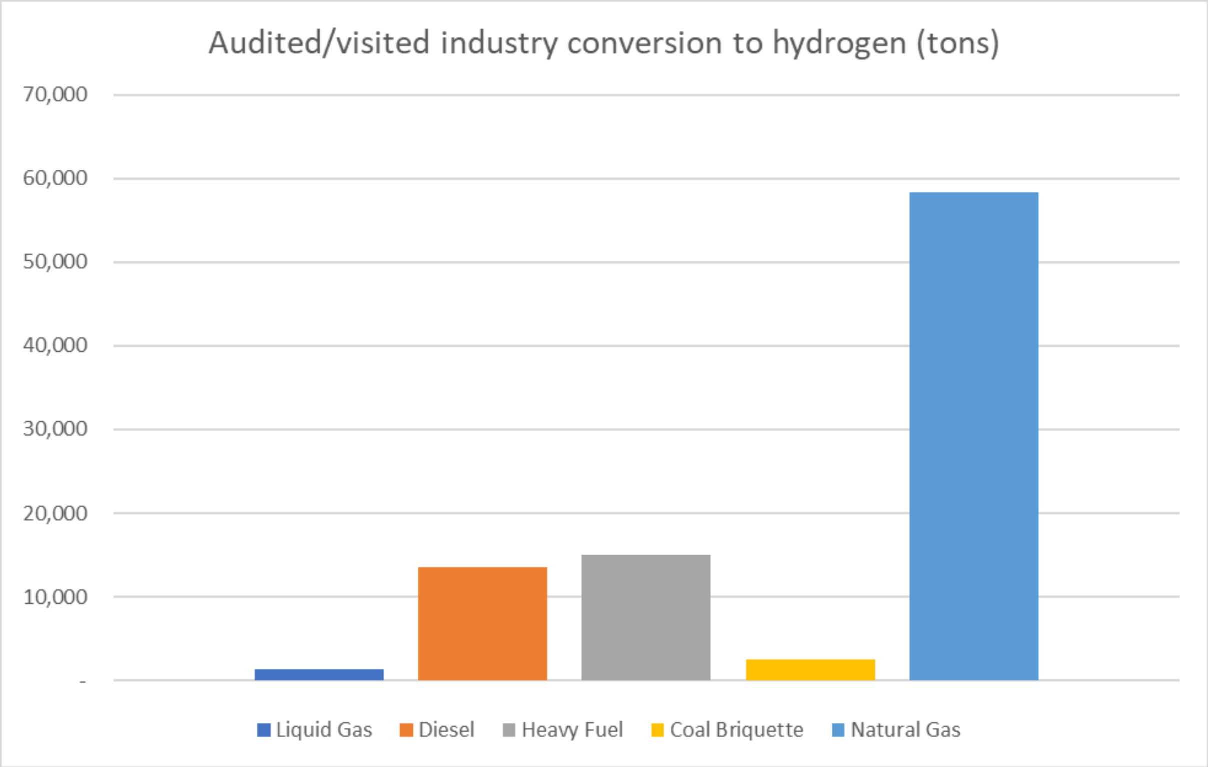


Figure 44 Audited/visited industry conversion to hydrogen (tons)

6.1 Key Pillars for the Decarbonization of Industrial Heating in Jordan

The transition to sustainable energy solutions offers Jordan an opportunity to enhance the competitiveness of its industrial sector while achieving significant decarbonization in the industrial heat sector. From this study, three key areas of impact are recommended in the following order of priority:

- **Energy efficiency and management:** Over 70 energy audits conducted in 2024 identified substantial inefficiencies and areas for improvement within factories. Building upon these audits can deliver both a reduction in emissions and operational savings.
- **Solar thermal and concentrated solar heating (CSH):** Industries with low to medium-temperature needs can adopt solar-based thermal solutions, which present a viable alternative to fossil fuels, taking advantage of Jordan's abundant solar resources.
- **Green hydrogen for hard-to-abate sectors:** For sectors that include steel, cement, and chemicals — where high-temperature heat is essential — green hydrogen offers a feasible decarbonization pathway. Green hydrogen, produced via electrolysis powered by renewable energy, aligns with Jordan's

goals to increase renewable penetration and energy independence. Green hydrogen may also be a backup for the ever-increasing adoption of natural gas.

6.2 Main Challenges and Opportunities for Green Hydrogen Adoption

This study demonstrates that green hydrogen production for the decarbonization of heating processes in the industrial sector is technically feasible. Optimal production estimates under net-metering and net-billing scenarios for medium and large industrial sectors are 1.95 JOD/kgH_2, 2.5 JOD/kgH_2, and 3.09 JOD/kgH_2, which corresponds to 2.75 USD/kgH_2, 3.53 USD/kgH_2, and 4.36 USD/kgH_2 respectively. However, the adoption of green hydrogen in Jordan faces several challenges, including high production costs compared to conventional fuels such as Natural Gas, infrastructure limitations, water scarcity, policy and regulatory gaps, and financial constraints.

While there are challenges to adopting green hydrogen in Jordan, there are also significant opportunities. The country's abundant renewable energy resources create a solid foundation for expanding production. Green hydrogen can also help make industries more competitive and open up new export opportunities as global markets increasingly focus on sustainability. Furthermore, developing shared infrastructure, improving production efficiency, introducing supportive policies, and fostering international collaboration can help overcome these barriers and accelerate the shift to a cleaner, low-carbon future. This study aims to explore the potential of green hydrogen in the industrial sector's thermal requirements. The main challenges and opportunities relevant to the Jordanian energy context are:

- **High production costs:** Green hydrogen production costs remain high compared to conventional fuels, even after accounting for taxes and distribution in fuel prices. However, advancements in electrolysis technology, along with findings from this report's sensitivity analysis, indicate that reducing LCOE, lowering electrolyzer costs, and improving efficiency which is evolving rapidly could significantly lower hydrogen production costs over time. On top of that, the global shift toward carbon pricing, exemplified by the EU's Carbon Border Adjustment Mechanism (CBAM) imposes costs on carbon-intensive exports, creating challenges for industries reliant on fossil fuels and presents an opportunity for Jordanian industries to transition to green hydrogen and other low-carbon technologies. This shift could enhance Jordan's export competitiveness and better align its industrial sector with global sustainability trends.

- **Water scarcity and infrastructure limitations:**

While the water scarcity and the infrastructure limitations are considered as main challenges for green hydrogen production in Jordan. The Aqaba Special Economic Zone (ASEZ) was selected as the central hub for green hydrogen production due to its access to seawater for desalination and its port for exporting hydrogen and its derivatives. Designated areas within ASEZ will host electrolyzers, derivatives production facilities, and desalination plants, while renewable electricity plants identified by MEMR will supply these installations, these locations are mainly in the southern part of the country close to good wind resources in Tafileh, and the solar potential in Ma'an. In addition to that, and in order to promote collaboration among developers MEMR intends to develop common-use infrastructure for GH2 projects that will be serve as a backbone for the projects slated for implementation in Jordan. This would create synergies, reduce redundancy, and optimize resource.

While detailed design plans for the various green hydrogen (GH2) project developers have not yet been published, it is evident that different developers are adopting distinct approaches to renewable technologies and the transport of electricity, water, hydrogen, or ammonia. These variations reflect diverse design philosophies tailored to specific project goals and operational requirements. However, identifying local industrial off-takers for hydrogen and green ammonia could help in optimizing these plans. By aligning production facilities and infrastructure routes with the needs of local industries, developers can enhance efficiency, reduce transportation challenges, and better integrate with the common-use infrastructure, supporting a more streamlined and cost-effective green hydrogen ecosystem in Jordan.

- **Policy and regulatory gaps:**

While efforts are underway to integrate a green hydrogen (GH2) strategy within Jordan's broader energy strategy, the absence of a published, clear regulatory framework and supportive policies continues to hinder the establishment of a GH2 market. To accelerate market creation, attract investments, and encourage private sector participation, it is essential to finalize and implement these strategies with specific regulations, incentives, and a detailed roadmap. Highlighting the Ministry's proactive role in this regard could provide momentum for further development.

- **Financial constraints:**

Although developers often bring both technology and funding to green hydrogen projects, financial constraints remain a significant challenge in Jordan. Misaligned contract durations, such as 10-year off-take agreements versus 20- to 25-year financing terms, increase financial risk and discourage investment. To mitigate these risks, it is important for governments to understand developers' needs, including clear policies, streamlined permitting, public-private co-financing, and guarantees to enhance bankability. Addressing these issues is crucial for overcoming financial barriers and accelerating green hydrogen deployment.

- **Technological maturity:**

Green Hydrogen: Two main categories summarize this barrier, the first is that green hydrogen production technology is still in its early stages, and the second is the compatibility of green hydrogen with a given fuel burning system (such as boiler burners and furnaces) may require modifications and calibrations to the equipment and other manufacturing line elements. Continued innovation is needed to enhance compatibility and efficiency.

Green ammonia for High-Temperature Industrial Processes:

Green ammonia holds significant promise as an alternative fuel for high-temperature industrial processes, where traditional fossil fuels dominate. Its combustion can achieve flame temperatures of up to 1,500°C (2,732°F), making it suitable for applications such as metal processing, glass manufacturing, and ceramics.

In regions like Aqaba, green ammonia production offers logistical advantages, particularly for industries nearby and those with existing ammonia storage infrastructure. These advantages position green ammonia as a potential regional solution. However, its adoption faces notable challenges. The production of green ammonia relies on the energy-intensive Haber-Bosch process, which increases costs and energy losses compared to the direct use of green hydrogen. Additionally, green ammonia boilers are still in the development phase, limiting their feasibility for immediate use in industrial heating.

To address these challenges, various initiatives are advancing green ammonia combustion technology:

- **Cardiff University's Ammonia-Powered Boiler Initiative:** This project aims to develop an ammonia boiler to replace carbon-heavy oil in off-grid industrial sites. Currently, in the testing phase, it seeks to demonstrate the technology's real-world application.
- **Green NH3 – CO2-neutral Boiler Project:** Led by Gas- und Wärme-Institut Essen e.V. (GWI) and SAACKE GmbH, this project focuses on creating a CO2-neutral boiler using green ammonia. The research tackles critical issues such as flame stability and nitrogen oxide (NOx) emissions, with the ultimate goal of delivering a production-ready NH3 burner system.

While promising, several challenges hinder the widespread use of green ammonia for industrial heating:

- **Flame Stability:** Ensuring stable combustion of ammonia at high temperatures is essential. Research is ongoing to enhance flame performance and reliability.
- **Nitrogen Oxide Emissions:** Combustion of ammonia can produce nitrogen oxides (NOx), harmful pollutants that require advanced low-NOx technologies to mitigate.
- **Commercial Availability:** Green ammonia boilers are still in the development stage, with limited availability hindering adoption for industrial processes.

Despite these challenges, the potential benefits of green ammonia, including reduced carbon emissions and integration with renewable energy sources, make it a compelling option for the future of high-temperature industrial applications. Continued research and development, supported by projects like those at Cardiff University and GWI, are essential to overcome these barriers and unlock the full potential of green ammonia as a sustainable alternative in industrial processes.

6.3 Preliminary Road Map

While the government has signed 14 MOUs for green hydrogen production for export from Aqaba, it is equally vital to explore domestic utilization of green hydrogen to decarbonize industrial process heating.

This roadmap outlines the phased implementation of green hydrogen in Jordan’s industrial sector, with timelines categorized into short-term (up to 2030), medium-term (up to 2040), and long-term (up to 2050). Each phase focuses on specific milestones to ensure a systematic and sustainable approach. The plan aims to leverage Jordan's abundant renewable energy resources, strategic geographic location, and existing industrial infrastructure to create a sustainable and economically viable hydrogen economy. This roadmap introduces a “win-win-win” model, where the government accepts part of the green hydrogen production in place of financial fees and redistributes this hydrogen to local industries at subsidized prices. This approach ensures that the hydrogen production companies, industries, and government all benefit, fostering sustainable economic growth, decarbonization, and energy security. It must be emphasized that further analysis must be conducted to develop a comprehensive business model that ensures the successful and sustainable roll-out of green hydrogen into the industrial sector.

6.3.1 Short-Term Recommendations (up to 2030)

Implement the Win-Win-Win model:

- Adjust tax policies to allow green hydrogen production companies to pay part of their dues in hydrogen instead of cash (such as corporate taxes, royalties, and license fees).

2 Secure early demand for hydrogen producers, reducing financial risks while ensuring a stable hydrogen supply for local industries.

Pilot projects and local industry engagement:

- Launch pilot projects in steel, cement, and chemical industries, using hydrogen from Aqaba to test hydrogen-based industrial heating.
- Collaborate with hydrogen producers to allocate initial production volumes to local industrial uses.

Infrastructure planning and coordination:

- Coordinate with hydrogen producers to utilize shared desalination infrastructure for sustainable water supply to hydrogen plants.
- Design pilot hydrogen hubs near key industrial zones to streamline hydrogen distribution for heating applications.

Capacity building and awareness:

- Train industrial operators and engineers on hydrogen-based heating technologies and prepare industries for hydrogen integration.
- Promote the subsidized hydrogen program as a competitive alternative to conventional fossil fuels.

6.3.2 Mid-term recommendations (up to 2040)

Develop hydrogen hubs and distribution networks:

- Build hydrogen infrastructure connecting Aqaba to major industrial zones, ensuring consistent supply for industrial users.
- Incorporate hydrogen blending into the natural gas pipeline network, using green hydrogen to enhance energy security and extend the 60-day emergency energy reserve [63].

Expand the subsidized hydrogen program:

- Use hydrogen acquired through the win-win-win model to secure long-term supply agreements with local industries at competitive rates.
- Encourage industries to retrofit equipment for hydrogen-based heating.

Financial incentives and partnerships:

- Provide grants, low-interest loans, and tax credits to incentivize hydrogen-based heating solutions.
- Foster public-private partnerships (PPPs), to co-finance hydrogen infrastructure with support from climate funds and international investments

Integrate renewable energy with hydrogen production:

- Promote renewable-hydrogen hybrid solutions, such as solar thermal systems combined with hydrogen, to optimize heating efficiency in industries. Align hydrogen production with expanded renewable energy capacity to ensure affordability and sustainability.

6.3.3 Long-term recommendations (up to 2050)

Scale domestic and export-oriented hydrogen markets:

- Position Jordan as a regional hub for hydrogen production, balancing export demand with local industrial needs.
- Use part of the export revenues to subsidize hydrogen for domestic industries, ensuring long-term affordability and competitiveness.

Strengthening energy security with hydrogen blending:

- Scale up hydrogen blending in the natural gas grid to enhance the emergency energy reserve and reduce dependency on imported fossil fuels.
- Establish regional partnerships to share hydrogen infrastructure and facilitate seamless cross-border hydrogen distribution.

Standardize hydrogen infrastructure and technology:

- Develop hydrogen-ready standards for industrial equipment to encourage a smooth transition from natural gas to hydrogen.
- Promote local manufacturing of hydrogen-related components, such as burners and storage systems, to create jobs and foster innovation.

Monitor impact and adjust policies:

- Continuously evaluate the impact of the win-win-win model and adapt subsidies, quotas, or policies to balance industrial, governmental, and export objectives.
- Integrate hydrogen development into Jordan's long-term energy strategy, ensuring alignment with national climate goals and economic priorities.

Conclusion

As outlined in this roadmap, green hydrogen adoption represents a transformative opportunity for Jordan, fostering sustainability and economic resilience. For the government, green hydrogen reduces fiscal pressures, strengthens energy security, and generates new revenue streams. Hydrogen production companies benefit from predictable demand and favorable investment conditions, while local industries gain access to cost-effective, sustainable fuels that enhance their competitiveness in a low-carbon economy.

These synergies underscore green hydrogen's potential to drive economic growth, environmental progress, and energy security in Jordan, positioning the country as a key player in industrial decarbonization and a major contributor to the global hydrogen market.

7 References

[1] "Jordan - Renewable Energy." Accessed: Oct. 29, 2024. [Online]. Available: https://www.trade.gov/country-commercial-guides/jordan-renewable-energy

[2] S. R. Ersoy and J. Terrapon-Pfaff, "SUSTAINABLE TRANSFORMATION OF JORDAN'S ENERGY SYSTEM Development of a Phase Model Climate Change, Energy and Environment," 2021.

[3] Ministry of Energy and Mining Resources, "Summary of Jordan Energy Strategy 2020-2030." Accessed: Oct. 30, 2024. [Online]. Available: https://www.memr.gov.jo/EBV4.0/Root_Storage/EN/EB_Info_Page/StrategyEN2020.pdf

[4] "Energy Ministry signs MoUs for oil exploration, green hydrogen development | Jordan Times." Accessed: Oct. 30, 2024. [Online]. Available: https://jordantimes.com/news/local/energy-ministry-signs-mous-oil-exploration-green-hydrogen-development

[5] A. Wucke, A. Aslam, and A. Almarzouq, "SECTOR ANALYSIS-JORDAN, GREEN HYDROGEN FOR THE COMMERCIAL AND INDUSTRIAL (C&I) SECTOR 2," Berlin, 2023. Accessed: Oct. 09, 2024. [Online]. Available: www.giz.de/en

[6] "Jordan Chamber of Industry." Accessed: Oct. 09, 2024. [Online]. Available: https://jci.org.jo/Chamber/sectors?l=en

[7] "2025 mineral resources strategy aims for 11% GDP contribution for mining sector | Jordan Times." Accessed: Dec. 21, 2024. [Online]. Available: https://jordantimes.com/news/business/2025-mineral-resources-strategy-aims-11-gdp-contribution-mining-sector

[8] "The Use of Hydrogen as an industrial feedstock in the Jordanian Chemical Industry-Market Analysis & Outlook," 2023. [Online]. Available: www.alokab.co

[9] N. Rambhujun *et al.*, "Renewable hydrogen for the chemical industry," *MRS Energy and Sustainability*, vol. 7, no. 1, pp. 1–16, Dec. 2020, doi: 10.1557/MRE.2020.33/FIGURES/5.

[10] H. Muhsen, M. Al-Mahmodi, R. Tarawneh, A. Alkhraibat, and A. Al-Halhouli, "The Potential of Green Hydrogen and Power-to-X Utilization in Jordanian Industries: Opportunities and Future Prospects," *Energies 2024, Vol. 17, Page 213*, vol. 17, no. 1, p. 213, Dec. 2023, doi: 10.3390/EN17010213.

[11] Alokab, GIZ, IKI, and International PtX Hub, “The Use of Hydrogen as an industrial feedstock in the Jordanian Chemical Industry-Market Analysis & Outlook,” Dec. 2023. Accessed: Nov. 16, 2024. [Online]. Available: pth-hub.org

[12] M. Jaradat, O. Alsotary, A. Juaidi, A. Albatayneh, A. Alzoubi, and S. Gorjian, “Potential of Producing Green Hydrogen in Jordan,” *Energies 2022, Vol. 15, Page 9039*, vol. 15, no. 23, p. 9039, Nov. 2022, doi: 10.3390/EN15239039.

[13] C. Baldino, J. O’Malley, S. Searle, and A. Christensen, “Hydrogen for heating? Decarbonization options for households in the European Union in 2050,” 2021. [Online]. Available: www.theicct.org

[14] J. Rosenow, “A meta-review of 54 studies on hydrogen heating,” *Cell Reports Sustainability*, vol. 1, no. 1, p. 100010, Jan. 2024, doi: 10.1016/J.CRSUS.2023.100010.

[15] A. Ajanovic, M. Sayer, and R. Haas, “The economics and the environmental benignity of different colors of hydrogen,” *Int J Hydrogen Energy*, vol. 47, no. 57, pp. 24136–24154, Jul. 2022, doi: 10.1016/J.IJHYDENE.2022.02.094.

[16] “Hydrogen Produced from Methane Pyrolysis: Key Considerations for Investors.” Accessed: Nov. 16, 2024. [Online]. Available: https://www.third-derivative.org/blog/hydrogen-produced-from-methane-pyrolysis-key-considerations-for-investors

[17] N. Sánchez-Bastardo, R. Schlögl, and H. Ruland, “Methane Pyrolysis for Zero-Emission Hydrogen Production: A Potential Bridge Technology from Fossil Fuels to a Renewable and Sustainable Hydrogen Economy,” *Ind Eng Chem Res*, vol. 60, no. 32, pp. 11855–11881, Aug. 2021, doi: 10.1021/ACS.IECR.1C01679/ASSET/IMAGES/LARGE/IE1C01679_0008.JPEG.

[18] D. Pashchenko, “Green hydrogen as a power plant fuel: What is energy efficiency from production to utilization?,” *Renew Energy*, vol. 223, p. 120033, Mar. 2024, doi: 10.1016/J.RENENE.2024.120033.

[19] PtX Hub, “PtX.Sustainability Dimensions and Concerns,” 2021. Accessed: Dec. 22, 2024. [Online]. Available: https://ptx-hub.org/wp-content/uploads/2022/05/PtX-Hub-PtX.Sustainability-Dimensions-and-Concerns-Scoping-Paper.pdf

[20] F. Rizzi, N. J. van Eck, and M. Frey, "The production of scientific knowledge on renewable energies: Worldwide trends, dynamics and challenges and implications for management," *Renew Energy*, vol. 62, pp. 657–671, Feb. 2014, doi: 10.1016/J.RENENE.2013.08.030.

[21] F. Liu, B. Hu, R. Li, and Y. Li, "A Novel Control Strategy of Energy Storage System Considering Prediction Errors of Photovoltaic Power," *2018 15th International Conference on Control, Automation, Robotics and Vision, ICARCV 2018*, pp. 1247–1251, Dec. 2018, doi: 10.1109/ICARCV.2018.8581299.

[22] International Energy Agency, "Global Hydrogen Review 2024 – Analysis - IEA." Accessed: Oct. 09, 2024. [Online]. Available: https://www.iea.org/reports/global-hydrogen-review-2024

[23] U. Chavan, "Calorific value calculation for natural gas -hydrogen blend," *Other resources*, Oct. 2022, doi: https://doi.org/10.17632/8hkd68ppgm.1.

[24] E. Beguedou, S. Narra, E. Afrakoma Armoo, K. Agboka, and M. K. Damgou, "Alternative Fuels Substitution in Cement Industries for Improved Energy Efficiency and Sustainability," *Energies 2023, Vol. 16, Page 3533*, vol. 16, no. 8, p. 3533, Apr. 2023, doi: 10.3390/EN16083533.

[25] "Hydrogen-Fueled Gas Turbines | GE Vernova." Accessed: Feb. 11, 2025. [Online]. Available: https://www.gevernova.com/gas-power/future-of-energy/hydrogen-fueled-gas-turbines

[26] F. B. Juangsa, A. S. Cezeliano, P. S. Darmanto, and M. Aziz, "Thermodynamic analysis of hydrogen utilization as alternative fuel in cement production," *S Afr J Chem Eng*, vol. 42, pp. 23–31, Oct. 2022, doi: 10.1016/J.SAJCE.2022.07.003.

[27] M. H. C. Cavalcanti *et al.*, "Hydrogen in Burners: Economic and Environmental Implications," *Processes 2024, Vol. 12, Page 2434*, vol. 12, no. 11, p. 2434, Nov. 2024, doi: 10.3390/PR12112434.

[28] Lafarge Cement Jordan, "Lafarge Cement Jordan - Annual Report 2023," 2023. Accessed: Oct. 09, 2024. [Online]. Available: https://www.lafarge.com.jo/sites/jordan/files/docs/e-lafarge-annual-report-2023.pdf

[29] JPMC, "JPMC - Sustainability Report 2023," 2023. Accessed: Oct. 09, 2024. [Online]. Available:

https://jpmc.com.jo/ebv4.0/root_storage/en/eb_list_page/jpmc_english_consolidated_sustainability_report.pdf

[30] Arab PotAsh Company, “APC - SUSTAINABILITY REPORT 2023 PARTNERS IN GLOBAL FOOD INDUSTRY,” 2023. Accessed: Oct. 09, 2024. [Online]. Available: https://arabpotash.com/ebv4.0/root_storage/en/eb_list_page/apc_2023_sustainability_report-english.pdf

[31] “Fajr Company, Jinsheng International’s Ceramics Factory sign agreement | Jordan Times.” Accessed: Oct. 09, 2024. [Online]. Available: https://jordantimes.com/news/local/fajr-company-jinsheng-internationals-ceramics-factory-sign-agreement

[32] Ministry of Energy and Mineral Resources, “Energy Balance Statistics Report 2023,” 2023. Accessed: Oct. 16, 2024. [Online]. Available: https://www.memr.gov.jo/ebv4.0/root_storage/ar/eb_list_page/energybalance2023.pdf

[33] “Accelerating NDC Implementation to Achieve Jordan`s Ambitious 31% Emissions Reduction Target | Department of Economic and Social Affairs.” Accessed: Oct. 20, 2024. [Online]. Available: https://sdgs.un.org/partnerships/accelerating-ndc-implementation-achieve-jordans-ambitious-31-emissions-reduction

[34] “Jordan’s Fourth National Communication on Climate Change | United Nations Development Programme.” Accessed: Oct. 20, 2024. [Online]. Available: https://www.undp.org/jordan/publications/jordans-fourth-national-communication-climate-change

[35] “Energy and Minerals Regulatory Commission-EMRC - | Who’s Who in Jordan’s Energy, Water & Enviroment 2019.” Accessed: Oct. 30, 2024. [Online]. Available: https://jordanewe.com/2022/about-sector/energy-and-minerals-regulatory-commission-emrc

[36] “Law No. 11 of 2018 Petroleum Products Law.” Accessed: Oct. 30, 2024. [Online]. Available: https://www.memr.gov.jo/ebv4.0/root_storage/en/eb_list_page/law_no._11_of_2018_petroleum_products_law-0.pdf

[37] EMRC, “نظام معدل لنظام ترخيص المشتقات البترولية - Amended System for Licensing Petroleum Derivatives 2023,” 2023. Accessed: Oct. 30, 2024. [Online]. Available: https://emrc.echo.jo/ebv4.0/root_storage/ar/eb_list_page/%D9%86%D8%B8%D8%A7%D9%85_%D9%85%D8%B9%D8%AF%D9%84_%D9%84%D9%86%D8%B8%D8%A7%D9%85_%D8%AA%D8%B1%D8%AE%D9%8A%D8%B5_%D8%A7%D9%84%D9%85%D8%B4%D8%AA%D9%82%D8%A7%D8%AA_%D8%A7%D9%84%D8%A8%D8%AA%D8%B1%D9%88%D9%84%D9%8A%D8%A9-1.pdf

[38] MEMR, “نظام تسعير المشتقات البتروابة - Petroleum Derivatives Pricing System,” 2019. Accessed: Oct. 30, 2024. [Online]. Available: https://www.memr.gov.jo/AR/List/%D8%A7%D9%84%D8%A7%D9%86%D8%B8%D9%85%D8%A9

[39] EMRC, “ تعليمات الحصول على تصريح و/أو رخصة نشاط شراء الغاز الطبيعي وضغطه وتسييله ونقله وتعبئته وتخزينه وتفريغه وتوزيعه وبيعه بالجملة والتجزئة لسنة 2022 - Instructions for Obtaining a Permit and/or License for Natural Gas Purchase Activities, Compression, Liquefaction, Transportation, Storage, Distribution, and Wholesale and Retail Sale for the Year 2022,” 2022. Accessed: Oct. 30, 2024. [Online]. Available: https://www.emrc.gov.jo/

[40] MEMR, “2024 نظام تنظيم ربط منشآت مصادر الطاقة المتجددة على النظام الكهربائي لعام - Regulation for Connecting Renewable Energy Facilities to the Electrical System for the Year 2024,” 2024. Accessed: Oct. 30, 2024. [Online]. Available: https://www.memr.gov.jo/ebv4.0/root_storage/ar/eb_list_page/5948-0.pdf

[41] Tom Smolinka *et al.*, “Industrialisierung der Wasserelektrolyse in Deutschland: Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme,” Berlin, 2018. Accessed: Oct. 29, 2024. [Online]. Available: https://www.ipa.fraunhofer.de/content/dam/ipa/de/documents/Publikationen/Studien/Studie-IndWEDe.pdf

[42] “Levelised Cost of Hydrogen Calculator.” Accessed: Oct. 29, 2024. [Online]. Available: https://www.agora-energiewende.org/data-tools/levelised-cost-of-hydrogen-calculator

[43] “System Advisor Model - SAM.” Accessed: Oct. 29, 2024. [Online]. Available: https://sam.nrel.gov/

[44] O. Ayadi, B. Rinchi, S. Al-Dahidi, M. E. B. Abdalla, and M. Al-Mahmodi, "Techno-Economic Assessment of Bifacial Photovoltaic Systems under Desert Climatic Conditions," *Sustainability 2024, Vol. 16, Page 6982*, vol. 16, no. 16, p. 6982, Aug. 2024, doi: 10.3390/SU16166982.

[45] "JRC Photovoltaic Geographical Information System (PVGIS) - European Commission." Accessed: Oct. 29, 2024. [Online]. Available: https://re.jrc.ec.europa.eu/pvg_tools/en/

[46] GSA, "Global Solar Atlas," Global Solar Atlas. Accessed: Oct. 16, 2023. [Online]. Available: https://globalsolaratlas.info/download/jordan

[47] "Al Dhafrah Solar Power Project | Abu Dhabi." Accessed: Oct. 29, 2024. [Online]. Available: https://www.adpv2.ae/

[48] "Mono Multi Solutions 0~+5W Comprehensive Products and System Certiicates," 2022, Accessed: Oct. 29, 2024. [Online]. Available: www.trinasolar.com

[49] "to change without notice. Version 1.5.4 SG250HX Multi-MPPT String Inverter for 1500 Vdc System," 2020.

[50] International Renewable Energy Agency, "RENEWABLE POWER GENERATION COSTS IN 2022," 2023. [Online]. Available: www.irena.org

[51] D. Feldman *et al.*, "Fall 2023 Solar Industry Update," 2023.

[52] C. Martínez de León, C. Ríos, and J. J. Brey, "Cost of green hydrogen: Limitations of production from a stand-alone photovoltaic system," *Int J Hydrogen Energy*, vol. 48, no. 32, pp. 11885–11898, Apr. 2023, doi: 10.1016/J.IJHYDENE.2022.05.090.

[53] C. Schnuelle, T. Wassermann, D. Fuhrlaender, and E. Zondervan, "Dynamic hydrogen production from PV & wind direct electricity supply – Modeling and techno-economic assessment," *Int J Hydrogen Energy*, vol. 45, no. 55, pp. 29938–29952, Nov. 2020, doi: 10.1016/J.IJHYDENE.2020.08.044.

[54] J. J. C. Mancera, F. S. Manzano, J. M. Andújar, F. J. Vivas, and A. J. Calderón, "An Optimized Balance of Plant for a Medium-Size PEM Electrolyzer: Design, Control and Physical Implementation," *Electronics 2020, Vol. 9, Page 871*, vol. 9, no. 5, p. 871, May 2020, doi: 10.3390/ELECTRONICS9050871.

[55] G. Barigozzi, G. Brumana, G. Franchini, E. Ghirardi, and S. Ravelli, "Techno-economic assessment of green hydrogen production for steady supply to

industrial users," *Int J Hydrogen Energy*, vol. 59, pp. 125–135, Mar. 2024, doi: 10.1016/J.IJHYDENE.2024.02.033.

[56] "Levelised cost of hydrogen Making the application of the LCOH concept more consistent and more useful", Accessed: Oct. 29, 2024. [Online]. Available: www.agora-industry.org

[57] E. Crespi, P. Colbertaldo, G. Guandalini, and S. Campanari, "Design of hybrid power-to-power systems for continuous clean PV-based energy supply," *Int J Hydrogen Energy*, vol. 46, no. 26, pp. 13691–13708, Apr. 2021, doi: 10.1016/J.IJHYDENE.2020.09.152.

[58] S. M. Saba, M. Müller, M. Robinius, and D. Stolten, "The investment costs of electrolysis – A comparison of cost studies from the past 30 years," *Int J Hydrogen Energy*, vol. 43, no. 3, pp. 1209–1223, Jan. 2018, doi: 10.1016/J.IJHYDENE.2017.11.115.

[59] J. Proost, "Critical assessment of the production scale required for fossil parity of green electrolytic hydrogen," *Int J Hydrogen Energy*, vol. 45, no. 35, pp. 17067–17075, Jul. 2020, doi: 10.1016/J.IJHYDENE.2020.04.259.

[60] "GREEN HYDROGEN COST REDUCTION SCALING UP ELECTROLYSERS TO MEET THE 1.5°C CLIMATE GOAL H 2 O 2," 2020, Accessed: Oct. 16, 2024. [Online]. Available: www.irena.org/publications

[61] "Delegated regulation - 2023/1184 - EN - EUR-Lex." Accessed: Dec. 22, 2024. [Online]. Available: https://eur-lex.europa.eu/eli/reg_del/2023/1184/oj

[62] "الجريدة الرسمية - رئاسة الوزراء." Accessed: Dec. 22, 2024. [Online]. Available: https://www.pm.gov.jo/Ar/Pages/NewsPaperDetails/5948

[63] "Jordan ready with alternatives in case of disruption in natural gas supplies — minister | Jordan Times." Accessed: Oct. 17, 2024. [Online]. Available: https://jordantimes.com/news/local/jordan-ready-alternatives-case-disruption-natural-gas-supplies-%E2%80%94-minister

Appendix A [Confidential]

[Confidential]

Figure 46 Photos of the internal process of steel-making.

The scrap metal is fed to the cauldron externally and after melting in the EAF is poured and shaped into standard billets that are cut at 6m lengths before either being stored and cooled to room temperature or fed directly to the rolling mills and finishing section of the factory.

Appendix B [Confidential]

Figure 47 Photos of [Confidential]

Appendix C [Confidential]

Figure 48 Photos of the [Confidential]

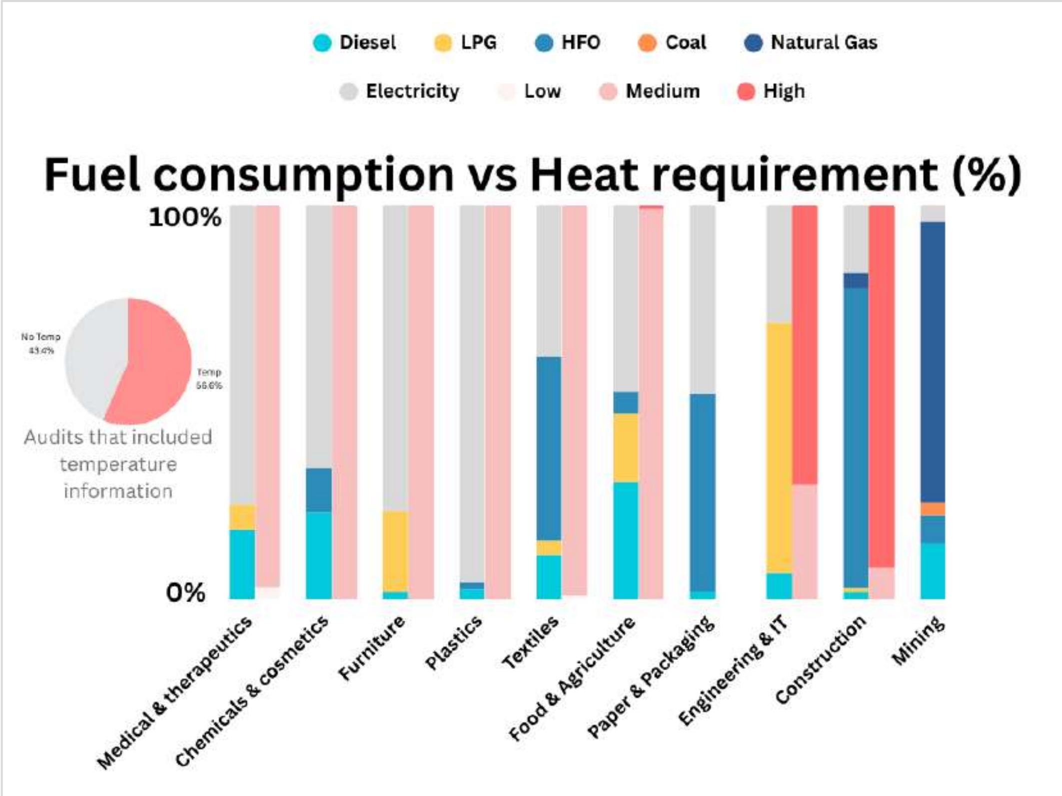
The images show the steam boiler and capture mechanism and the dryer barrel and rollers where the paper sheets are dried off before being prepped into final products

Appendix D Audited companies [Confidential]

Table 7 List of companies covered in the accessed energy audits

Figure 45 Photos from [Confidential]

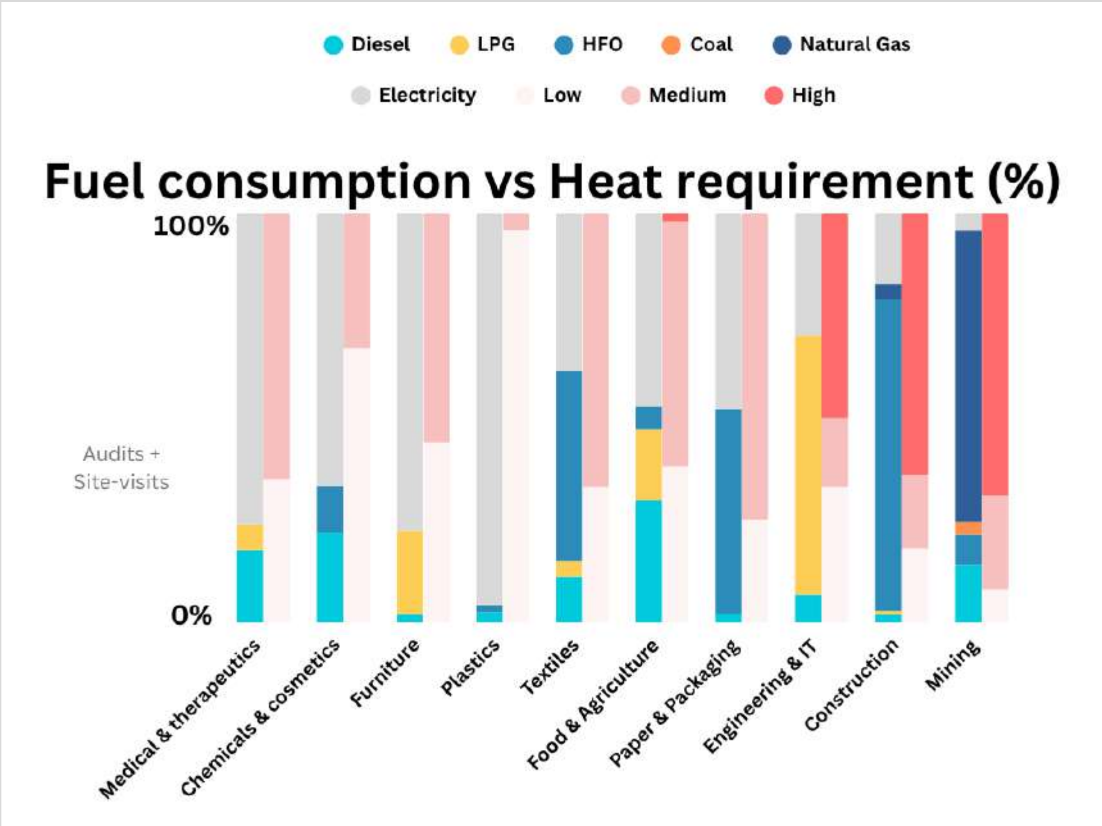
Appendix E Heat requirements clustering assumptions 1



Temperature range for each sector	low C <130	med C < 500	high C > 500
Medical & therapeutics	3%	97%	0%
Chemicals & cosmetics	0%	100%	0%
Technology Industry	0%	29%	71%
Furniture	0%	100%	0%
Plastics	0%	100%	0%
Textiles	1%	99%	0%
Food & Agriculture	0%	99%	1%
Paper & Packaging	0%	0%	0%
Construction	0%	8%	92%
Mining	0%	0%	0%

This is based on the count of reported thermal units (discarding capacity) and the temperature range they are expected to cover.

Appendix F Heat requirements clustering assumptions 2



Temperature range for each sector	low C <130	med C < 500	high C > 500
Medical & therapeutics	35%	65%	0%
Chemicals & cosmetics	67%	33%	0%
Technology Industry	33%	17%	50%
Furniture	44%	56%	0%
Plastics	96%	4%	0%
Textiles	33%	67%	0%
Food & Agriculture	38%	61%	2%
Paper & Packaging	25%	75%	0%
Construction	18%	18%	64%
Mining	8%	23%	69%

This is based on the count of temperature mentions in the audits from all companies. Where data is missing the temperatures assumed were based on the sector the company is from. The site visits also provided extra information that affected the paper & packaging, construction, and mining sector values.

Appendix G Fuel Prices JOPetrol

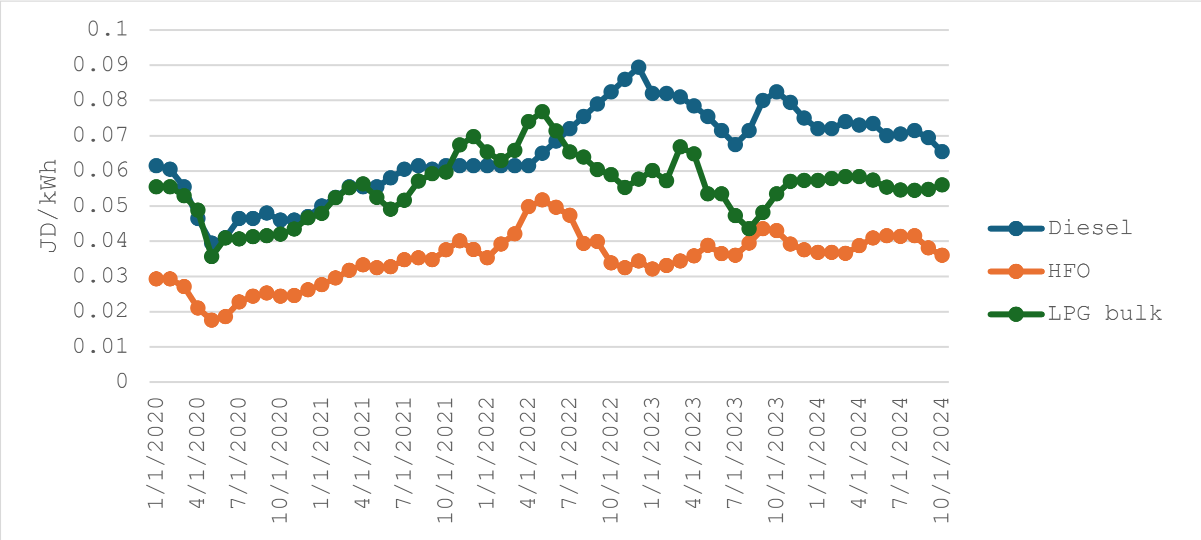


Figure 49 Fuel Prices per kWh from Jan 2020 till Oct 2024, JOPetrol

Appendix H Industrial sector energy consumption by fuel (ktoe)

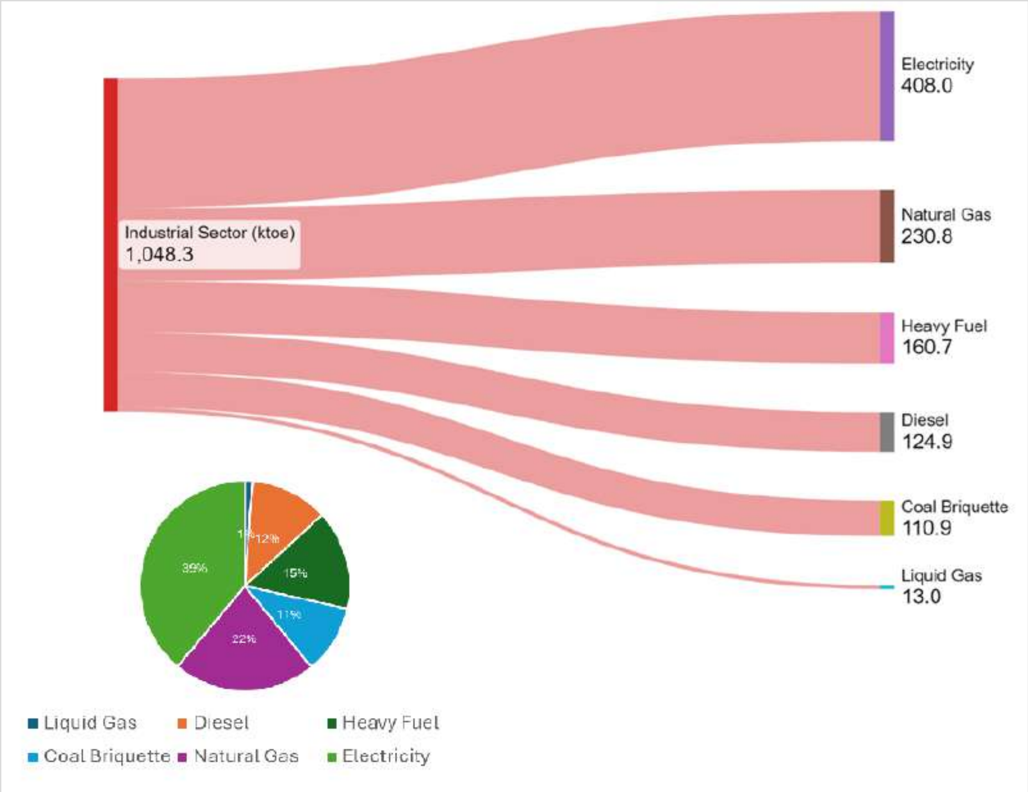


Figure 50 Breakdown of industrial sector energy consumption by fuel (ktoe), MEMR 2023 [32]

Appendix I On-Site walkthrough consumption

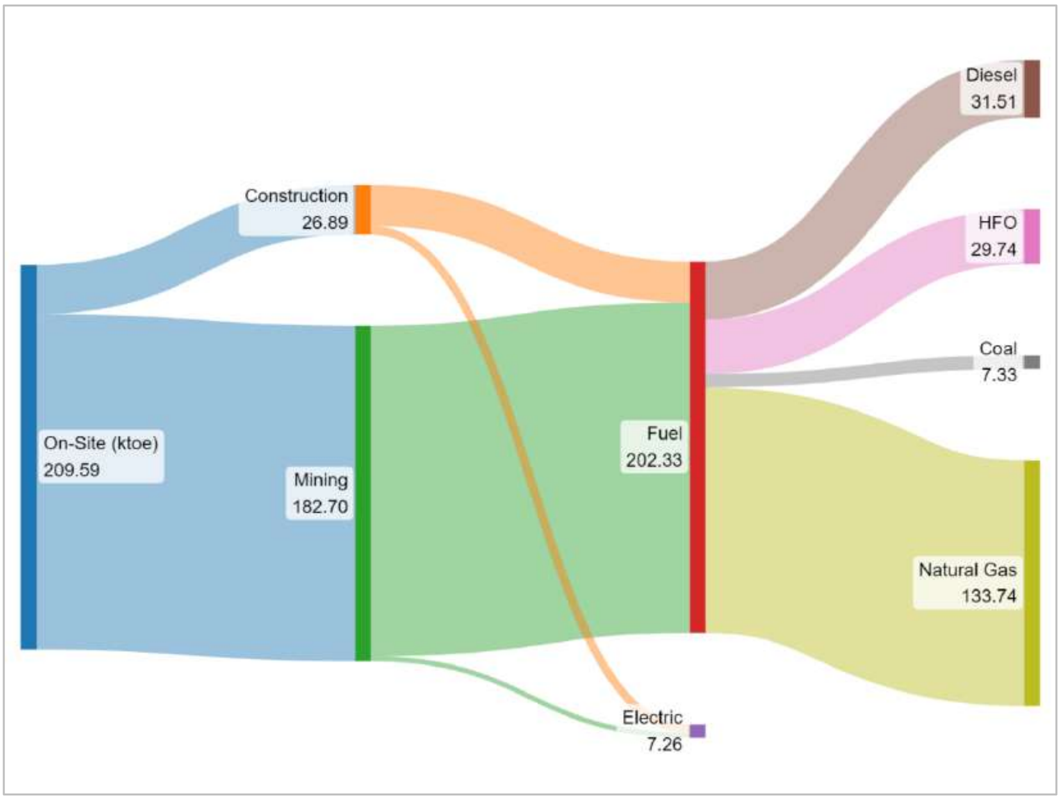


Figure 51 On-Site walkthrough consumption divided by electrical usage or other (ktoe)

Appendix J Published report analysis of consumption

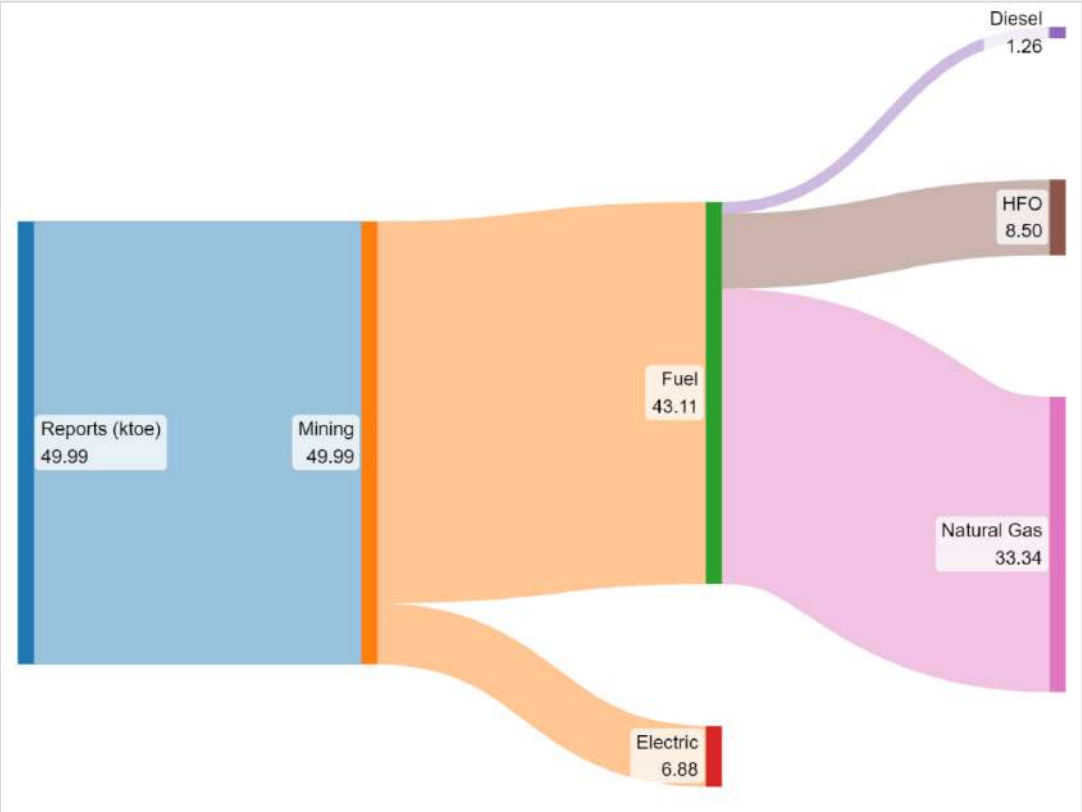


Figure 52 Published report analysis of consumption divided by electrical usage or other (ktoe)

Appendix K Analyzed consumption with fuel breakdown

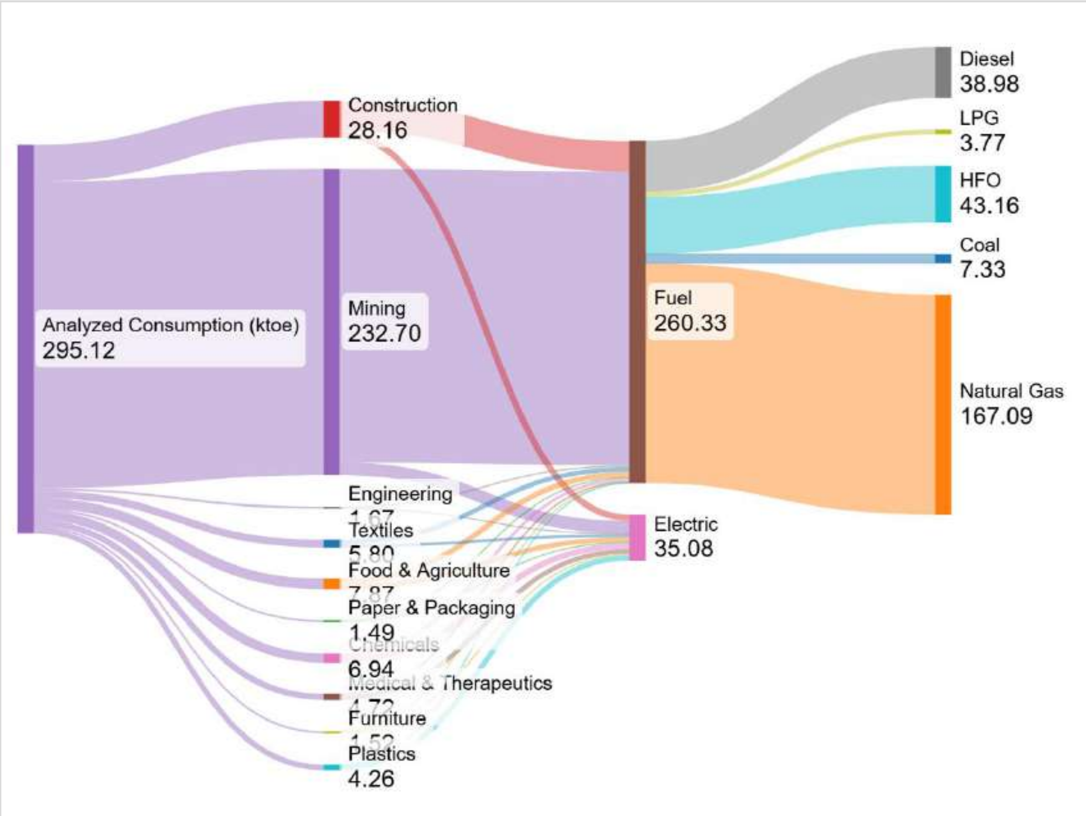


Figure 53 Analyzed consumption with fuel breakdown

Appendix L Industrial sector fuel consumption 2018 – 2023

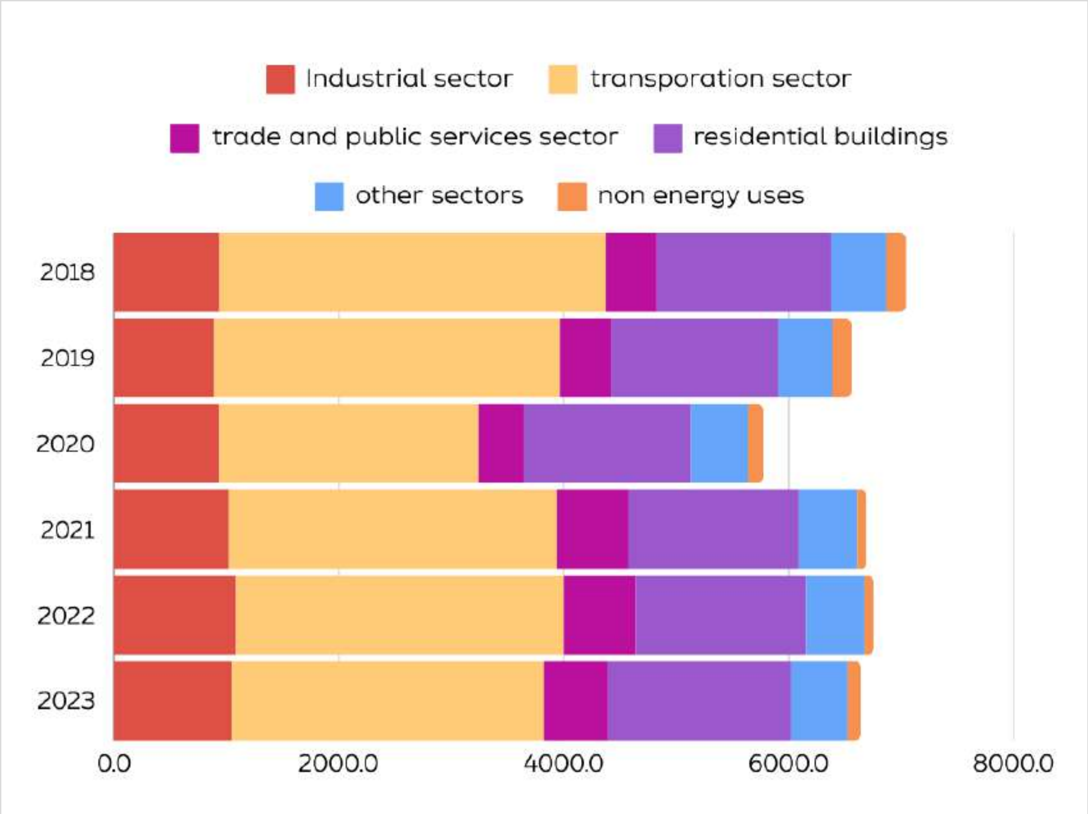


Figure 54 Industrial sector fuel consumption 2018 – 2023 in ktoe, MEMR

Appendix M Questionnaire

Survey: Evaluating the Potential of Using Green Hydrogen for Industrial Heating

1. Factory Information

- Factory Name:
- Date of construction
- Area of factory
- no. of employees
- Contact Information:
    - Name:
    - Email:
    - Phone Number:

2. Awareness and Interest in Green Hydrogen

3. Are you familiar with green hydrogen as a heating alternative?
    - [ ] Yes
    - [ ] No

4. How interested is your company in exploring green hydrogen for heating?
    - [ ] Very Interested
    - [ ] Somewhat Interested
    - [ ] Neutral
    - [ ] Somewhat Uninterested
    - [ ] Not Interested

5. What specific applications of green hydrogen for heating are you considering? (Select all that apply)
    - [ ] Process Heating
    - [ ] Steam Generation
    - [ ] Combined Heat and Power (CHP)
    - [ ] Other (please specify): __________

6. Current Energy Efficiency and Heating Processes

7. What is your primary heating source for industrial processes? (Select all that apply)
    - [ ] Natural Gas
    - [ ] Fuel Oil
    - [ ] Electricity
    - [ ] Diesel
    - [ ] LPG
    - [ ] Other (please specify): __________
8. What type of fuel storage and distribution systems do you currently use?

9. What is your current annual heating energy consumption (in MWh or fuel consumption liter, kg, m3,...)?

Month	2023	2024
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		

10. How are you measuring the fuel consumption (meters, submeters, energy bills, ...)

11. What types of heating processes do you currently utilize? (Select all that apply)
    - [ ] Direct Heating (furnace, kiln, oven, etc.)
    - [ ] Indirect Heating
    - [ ] Steam Heating
    - [ ] Hot Water Heating
    - [ ] Others (please specify): __________

12. What is the average temperature range required for your heating processes?
    - [ ] Below 100°C
    - [ ] 100°C - 250°C
    - [ ] 250°C - 500°C
    - [ ] Above 500°C
13. If you possess on-site energy generation, what are the technologies used and their associated capacity?

14. What percentage of your total energy consumption is used for heating? __________ %

15. What current measures are in place to improve energy efficiency in heating systems?

16.Future Heat Demand and Anticipated Changes

17. How do you anticipate your heating requirements will change in the next 5-10 years?
    - [ ] Increase significantly
    - [ ] Increase moderately
    - [ ] Stay the same
    - [ ] Decrease moderately

- [ ] Decrease significantly
- Estimate percentage increase? ________

18. What are the main drivers for changes in your heating requirements? (Select all that apply)
    - [ ] Production Expansion
    - [ ] Regulatory Changes
    - [ ] Technological Advancements
    - [ ] Sustainability Goals
    - [ ] Other (please specify): __________

19.Technical and Economic Feasibility

20. Is green hydrogen directly compatible with your current infrastructure?

21. What is the age and condition of your current heating system(s)?

22. What are the current costs associated with your heating sources?

23. Estimate the potential costs of transitioning to green hydrogen, including infrastructure modifications.
24. What potential financial savings do you anticipate from reduced fuel costs and possible incentives for using green hydrogen?

25.Sustainability and Environmental Impact

26. Does your factory have any existing policies related to energy and environmental sustainability?

27. Estimate the potential reduction in carbon emissions if green hydrogen is integrated into your processes?

28. Are you currently a part of any green company/designation/credit program? And if not, are you interested in this aspect of hydrogen adoption (e.g. for easier exports, etc.)?

29.Onsite hydrogen generation

30. For considering onsite hydrogen systems feasibility, what is your facility's current source of water and sourced volume? (include the costs if available)

31. How much onsite/offsite space is available to you now or soon to build a private hydrogen facility? (location if available)

32.Timeline and Implementation Plans

33. If hydrogen proves an improvement to your processes, what percentage improvement to the process or the overall cost would be actionable for your establishment?

34. Beyond the cost/benefit analysis, what other factors can prevent/incentivize your transition to hydrogen or hydrogen integration?

35. What is your timeline for considering a transition to green hydrogen?

- [ ] Within 1 Year
- [ ] 1-3 Years
- [ ] 3-5 Years
- [ ] More than 5 Years
- [ ] No Plans

36. Would you be open to participating in pilot projects or collaborations related to green hydrogen?
    - [ ] Yes
    - [ ] No

37.Monitoring and Evaluation

38. Do you currently have systems in place for monitoring energy usage and emissions?

39. Will additional monitoring equipment be required for a transition to green hydrogen?

40.Barriers to Adoption

41. What do you perceive as the main barriers to adopting green hydrogen for heating? (Select all that apply)
    - [ ] High Production Costs
    - [ ] Lack of Infrastructure
    - [ ] Technical Challenges
    - [ ] Regulatory Uncertainty
    - [ ] Limited Knowledge/Experience
    - [ ] Other (please specify): __________

42. What support would facilitate your transition to green hydrogen? (Select all that apply)
    - [ ] Financial Incentives
    - [ ] Technical Assistance
    - [ ] Training and Education
    - [ ] Research and Development Support
    - [ ] Policy Support
    - [ ] Other (please specify): __________

43.Recommendations

44. Provide a summary of the feasibility of adopting green hydrogen for industrial heating in your factory.

45. What are the next steps, including further studies, pilot programs, or immediate actions to prepare for a transition?