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Saudi Arabia's key energy export market opportunities
in light of climate change mitigation through hydrogen production and use

Global Hydrogen Diplomacy (H_2-Diplo)

Implemented by

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ABBREVIATIONS

ATR	Auto thermal reforming	**ICT**	Information and communications technology
BAPV	Building added photovoltaics	**IEA**	International Energy Agency
BAU	Business As Usual	**IRA**	Inflation reduction act (in USA)
BEV	Battery Electric Vehicles	**KSA**	Kingdom of Saudi Arabia
BIPV	Building-integrated photovoltaics	**LCE**	Low-carbon energy
CAPEX	Capital cost expenditures	**LCOE**	Levelized cost of electricity
CBAM	Carbon border adjustment mechanism (in EU)	**LOHC**	Liquid organic hydrogen carrier
CCfD	Carbon contracts for difference	**LHV**	Lower heating value
CCS	Carbon capture and storage	**LNG**	Liquefied natural gas
CCUS	Carbon capture and usage or storage	**LTA**	Revealed technological advantage
CNG	Compressed natural gas	**MCH**	Methylcyclohexane (a LOHC chemical)
COP	Coefficient of performance	**mtpa**	Metric tons per year
DAC	Direct air capture	**OPEX**	Operating cost expenditures
DRI	Direct reduction of iron	**PEM**	Proton exchange membrane
EEX	European Energy Exchange	**PtX / PtL / PtG**	Power-to-X / -Liquid / -Gas
EU	European Union	**PV**	Photovoltaic
FCEL	Fuel Cell Electric Vehicles	**RE**	Renewable energy/ies
FLH	Full-load hours	**RED**	Renewable energy directive
GDP	Gross domestic product	**RES**	Renewable energy system(s)
GHG	Greenhouse gasses	**RWGS**	Reverse water gas shift reaction
GW	Gigawatt	**SDG**	Sustainable development goals
GWh	Gigawatt hours	**SEC**	Saudi Electricity Company
H_2	Hydrogen	**SMR**	Steam methane reforming
HNO	Hydrogen network operator	**SOEC**	Solid oxide electrolyser cell
HRS	Hydrogen Refueling Station	**tpd**	Tons per day
HVDC	High voltage, direct current	**USD**	United States Dollars
Ibid.	Latin: ibidem; meaning “in the same place”	**WACC**	Weighted average cost of capital

Name	Prefix symbol	Power of ten
Zetta	Z	10^{21}
Exa	E	10^{18}
Peta	P	10^{15}
Tera	T	10^{12}
Giga	G	10^{9}
Mega	M	10^{6}
Kilo	k	10^{3}

$ indicates United States Dollar (USD).

Tons indicate metric tons. Mt refers to Million (metric) tons.

Further units and key conversion data are explained in the APPENDIX.

EXECUTIVE SUMMARY

To achieve the climate goals to which most countries have committed themselves in the Paris Climate Agreement, greenhouse gas (GHG) emissions must be drastically reduced worldwide. For that purpose, an increased focus on electrification is required, with electricity being generated predominantly from renewable energies.

A reshuffling in the energy landscape as we know is expected, with the use of fossil primary energy sources for combustion purposes to be gradually replaced for the generation of electricity and heat. Hard-to-abate industrial processes or applications cannot be fully electrified. This is where hydrogen and derivatives can play a significant role in the future. Hydrogen development, given its application across various industries, appears essential to meet net-zero GHG emission goals. Global hydrogen demand reached 94 Mt in 2021, but only about 1% of it was produced as low emission hydrogen – by electrolysis using power from renewable sources, also called “green hydrogen” (IEA 2022c).

Key off-taker markets in Asia and Europe are committed to reducing the combustion of fossil fuels in the future. Saudi Arabia exports oil and oil products as well as ammonia and methanol annually to major consumer countries in Asia and Europe with a turnover of several hundreds of billions of dollars. With the evolution of electric cars and heat pumps, the demand for fuels and energy carriers for combustion purposes is expected to decrease in the near future; however, the demand for petrochemical products as raw materials for the chemical and pharmaceutical industries will continue to rise. This is where hydrogen as a substitute for fossils in hard-to-abate sectors comes into play. Hydrogen can be used for industrial processes such as producing green steel, for cement, ammonia, urea or methanol production. Powered by conventional energy carriers like natural gas, oil or coal, these processes release significant amounts of GHG. In principle the CO_2 could be captured and stored – or utilized (CCUS), but this is still costly and consumes a huge amount of energy for CO_2´s compression and transport.

Already today, there is a significant market for shipping ammonia and methanol. These two commodities could soon be produced in a green form by using green hydrogen, which would itself be produced with renewable energy at attractive costs. Countries in general aspire to become more independent from energy imports as these can have a negative impact on a country’s GDP. Hence, instead of importing ammonia, many countries plan to produce green ammonia primarily for their domestic market. However, densely populated countries with a strong industrial output and correspondingly high energy consumption will further be dependent on imports of energy carriers. Several countries in Europe announced that they will also rely on the import of green or blue hydrogen, such as Belgium and Germany. In Asia, Japan and South Korea are already negotiating imports of hydrogen or ammonia and started first pilot projects. India, the world’s most populous country, is expected to continue to rely on imported energy sources in the long term due to a lack of energy transportation infrastructures and limited capacity to invest in renewable energy generation. China is currently consuming more than a quarter of the global primary energy. At such a high energy consumption rate, mainly based on the use of coal for electricity generation, it is hard to imagine how energy supply without imports of green or blue energy carriers could work out in the near future.

Saudi Arabia presents outstanding conditions for solar technologies. The output of PV systems in the Kingdom amounts to yields nearly twice that of comparable size in Germany. Already today, very low electricity prices for PPA and bids are in place in Saudi Arabia. Next, the potential for wind power is also excellent in the kingdom. The quantity of fresh water needed for hydrogen production per electrolysis can be produced by seawater desalination plants – a field in which Saudi Arabia is very experienced with.

The more complex commodities sold on the international markets are in a given value chain, the higher revenues must be. For instance, if methanol is needed as a commodity, it is better to produce green methanol directly in Saudi Arabia and export the methanol instead of exporting green hydrogen to produce methanol in the consumer countries. This also applies to green ammonia and green steel.

In sum, with its very low costs of renewable power generation, Saudi Arabia unfolds great potential to meet its own energy needs with solar and wind, and to export green hydrogen, green ammonia or other related products. The oil or gas spared is too valuable for combustion purposes only. Instead, it can be used for the more profitable production of plastics and high-quality petrochemical products, further creating sustainable jobs and securing long-term prosperity. With ambitious projects such as NEOM, Saudi Arabia is already treading the path to such a future.

In terms of potential future trade relation in the (green) hydrogen field, the following scenarios are probable: Saudi Arabia does present strong features to become a country of choice for hydrogen and its derivitates´ production, both domestic and exports purposes.

Strong established trade ties with energy-hungry Asian countries place the Kingdom in an advantageous position to continue fulfilling its role as energy provider. For geography-constrained Japan and South Korea, with their (nearly) insular situation and densely populated surface, energy imports will remain high on the agenda.

China and India, the most populous countries on earth, might satisfy to some extend part of their domestic energy thirst; however, **with the speed of their economic and industrial developments, energy imports will be maintained for the time ahead**.

Second behind China in terms of exports originating from Saudi Arabia, **the EU could use its existing trade ties as well with the Kingdom and expand them to new heights.** The immense potential in addition to energy versatility unfold by Saudi Arabia, from a hydrocarbons´ but also renewables´ perspective, transform it into an ideal interlocutor in the upcoming hydrogen race.

Huge investments are already being made in such production plants in many Gulf states and the first purchase contracts have been signed in Asia and Europe. In addition, regulations and a trading exchange platform like the EEX are being set up to steer the upcoming hydrogen market.

1 Introduction

1.1 Background

Saudi Arabia is one of the world's main oil exporters. The oil and gas sector accounts for about 50% of gross domestic product, and more than 70% of export earnings (GASTAT 2022). Led by China, Asian countries represent the lion-share of Saudi Arabian exports. European countries (the 27 as a block) follow suit as the second most important export market for Saudi petrol goods.

However, as countries worldwide ramp up measures to reach climate neutrality and to fight global warming in accordance with the Paris climate accord, global demand for conventional oil and gas products for combustion purposes is meant to decline over the next decades. A report by Wood Mackenzie suggests that if world leaders take decisive action to limit global warming to 2°C by 2050, oil demand could drop significantly. In their accelerated energy transition scenario, the energy market would become increasingly electrified, leading to a 70% decrease in oil demand from current levels by 2050 (CNBC 2021).

In the future, there will be a paradigm shift towards electrification, which will also enable highly efficient energy conversion, so that the total amount of primary energy could decrease under the premise of a frugal use of energy (sufficiency). The transition to electric vehicles in transport and the use of heat pumps to heat water and buildings exemplify this development. For Saudi Arabia – much like other fossil fuel economies – economic ties towards certain off-taker markets will likely evolve in the years ahead.

With the announced gradual replacement of oil and its derivative products in their energy, transport or industrial production processes, Saudi Arabia´s most important customers are expected to purchase less conventional fuel. This may result in the loss of substantial export revenues from trade in oil and its products in the future.

In a drive to diversify its economic tissue, Saudi Arabia intends to massively develop hydrogen production and its derivative products for domestic and export purposes. The country's vast gas resources for blue hydrogen production (with carbon capture and storage, CCS) and abundant solar radiation and wind speeds for producing green hydrogen (based on water electrolysis without emitting CO_2) as well as decade-long leadership in the energy sector make it a natural contender to become a global leader in the hydrogen economy. Today, the global market for carbon-neutral hydrogen and its derivates is still nascent but rapidly evolving. For Saudi Arabia, it could hold the promise of maintaining its role as one of the key energy providers for the world. At the same time, generating export revenues to add on and later offset those from fossil fuel exports.

This study intends to analyze the relevance of energy carriers´ exports for Saudi Arabia. Today annual trade revenues of about 200 billion $ (US dollar) are reached from exporting 'Mineral fuels, lubricants and related materials (77% of total Saudi Arabia's export value in the year 2019)[1]. Chemical products also contribute in a significant way to incomes from export (14% from products section 6 'Chemicals and related products, n.e.s.'), especially shipping ammonia and methanol.

The key target markets of these products are located in Asia and Europe. Along with a general regional look at Asia and Europe, the following key countries are investigated in more detail regarding their trade relations and collaboration with Saudi Arabia when considering energy demand and future energy

[1] Calculation based on GASTAT Table 7-4_16 for Section 4 'Mineral fuels, lubricants and related materials'

import dependency. For Asia, the following countries are considered: China, India, Japan and South Korea. For Europe, the focus is set on Germany, France, the UK, the Netherlands, and Belgium.

1.1.1 Need for action – the economic argument

The economic argument is based on the fact that renewable energies, like solar PV and wind, saw their costs of production diminish dramatically. For PV modules, this can be expressed by the so-called learning curve, which is shown in Figure 1: **each time the cumulative PV module production doubled, the price went down by about 23%**.

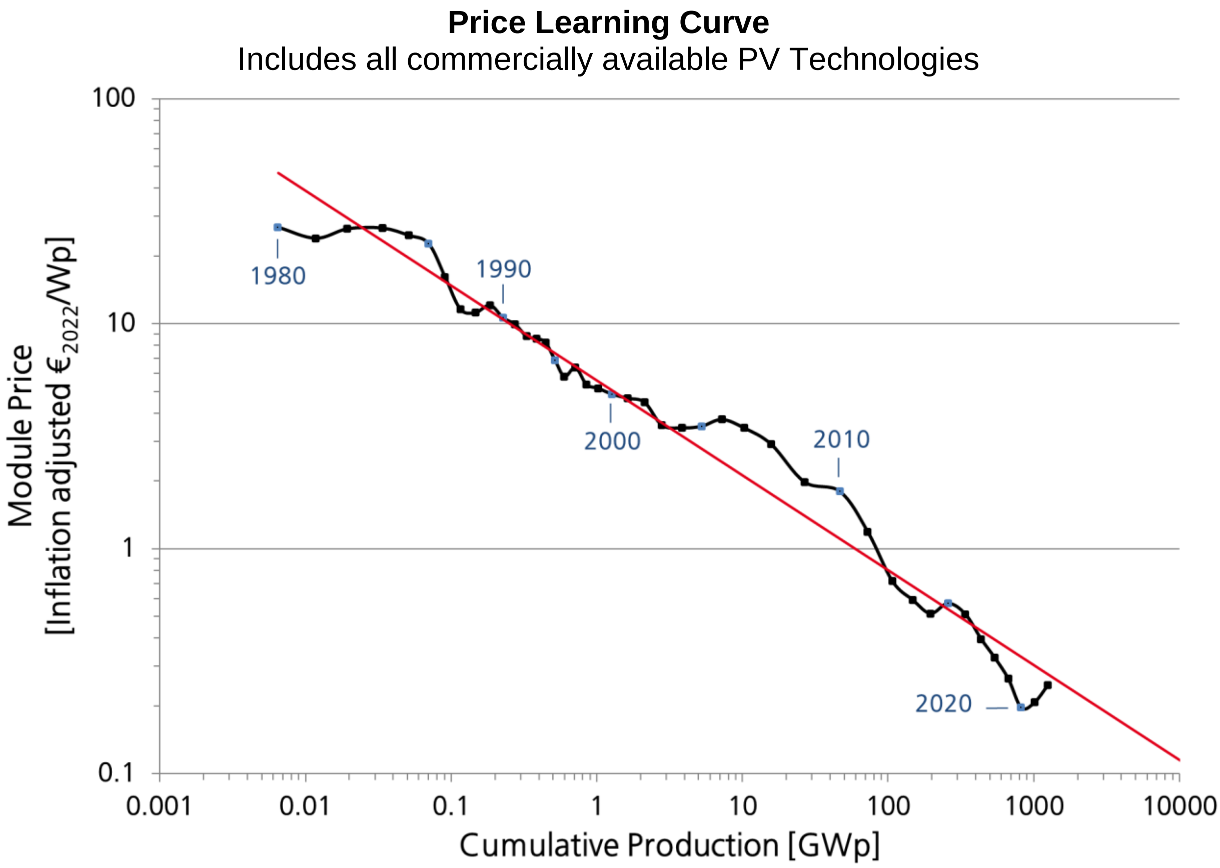


Figure 1: PV price learning curve

Source: (Fraunhofer ISE 2023, p 49)

This empirical insight has been true for the last 42 years, leading to the least cost of electricity generation with large utility-scale solar power plants. Lowest power purchase agreement (PPA) contracts was as low as 10.4 US$/MWh in Saudi Arabia, which is cheaper than any other power generation source (PV-Magazine 2021), (Commercialsolarguy 2021). A similar development was noticed with wind power systems as they have today a much higher capacity and energy output than 20 years ago as depicted in Figure 2.

The following four main parameters are critical for the production of hydrogen and derivates (PtX) from renewables to be economically viable:

- Cost of renewable electricity used in the process (levelized cost of electricity: LCOE),
- Electrolyser capital expenditure,
- Number of operating hours (load factor) on a yearly basis,
- Transport and storage considerations.

A country-specific evaluation is required to determine the economic viability. In this study, the focus is on the first (in the following section) and the last bullet point (see chapter 3.6.1).

LCOE of renewable energy sources

Cheap and plenty of renewable energy power is needed for hydrogen production. So the question remains whether Saudi Arabia has the capacity to generate it?

The global weighted-average levelized cost of electricity (LCOE) for onshore wind and utility-scale solar PV projects can be found in Figure 2. It must be noted that actual LCOE values can be significantly lower than the values depicted in the graph. This is true for specific locations with favorable conditions: high average wind density for wind power and high solar irradiation values throughout the year for PV systems. Figure 2 shows that for solar photovoltaic (PV) large ground-mounted power plants and onshore wind power systems the levelized costs of electricity (LCOE) and PPA tariffs or auction prices are already today below the cost range for power generation with fossil fuels. Concentrated solar power (CSP) and offshore wind systems are today in the cost range of power generation with fossil fuels and can be expected to be cheaper than those in the future thanks to steep learning curves.

The global weighted-average LCOE and PPA/auction prices for solar PV, CSP, onshore wind and offshore wind, 2010–2022

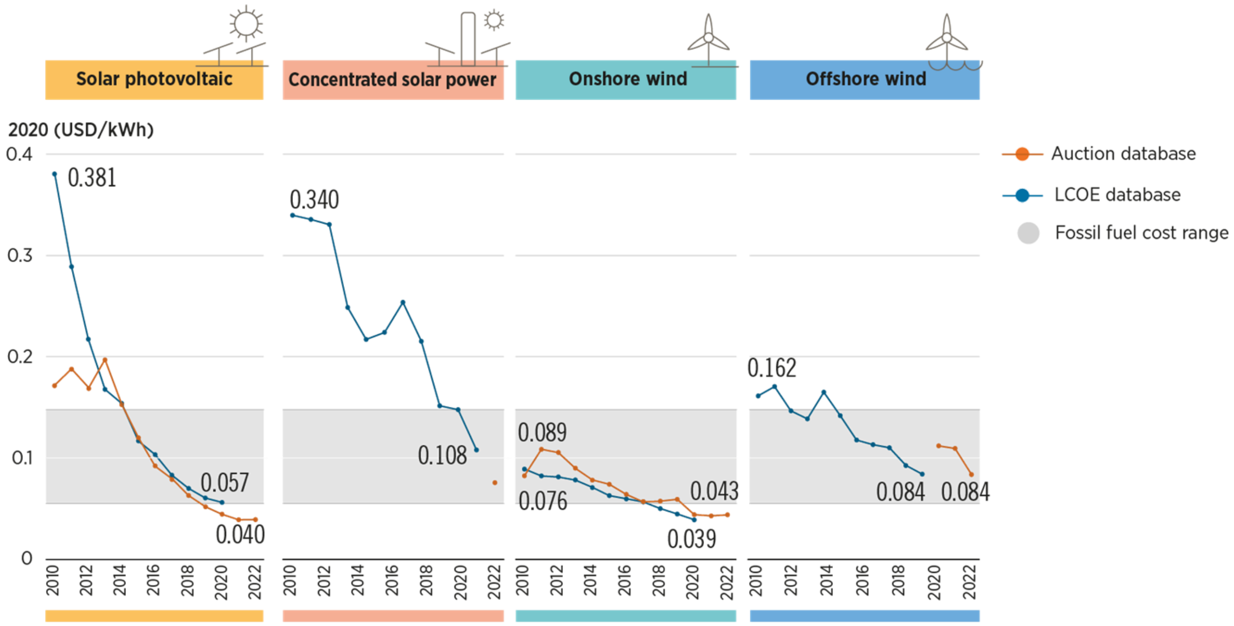


Figure 2: The global weighted-average LCOE and PPA/auction prices for solar PV, CSP, onshore wind and offshore wind

Source: (IRENA 2022b, p 45)

Renewable-based electricity is already the cheapest power option in most regions as can be found in Figure 2; this is especially true for solar PV and onshore wind systems. The global weighted-average LCOE of newly commissioned utility-scale solar PV projects fell by 85% between 2010 and 2020, that of CSP by 68%, onshore wind by 56% and offshore wind by 48%. All commercially available solar and wind technologies fall in the range of, or even undercut, the cost of electricity from newly built fossil-fuel plants. (IRENA 2022b, p 44). For Saudi Arabia, the cheapest source of new bulk electricity generation will be single-axis tracking PV systems with LCOE of 23 $/MWh reported in February 2022 (PROCESS 2022).

The reason for the detailed presentation of the LCOE is that very low electricity production costs have a strong influence on the costs of hydrogen production per electrolysis.

An analysis of CAPEX (mainly costs for electrolysers based on their full load hours) and OPEX (mainly costs for electricity and fresh water) are depicted in Figure 3: the sensitivity shows that with increasing full load hours, the impact of CAPEX on hydrogen costs declines and the **electricity becomes the main cost component for water electrolysis** (IEA 2019).

Sensitivity analysis for hydrogen production costs in 2030
for various investment costs, electricity prices and different full load hours

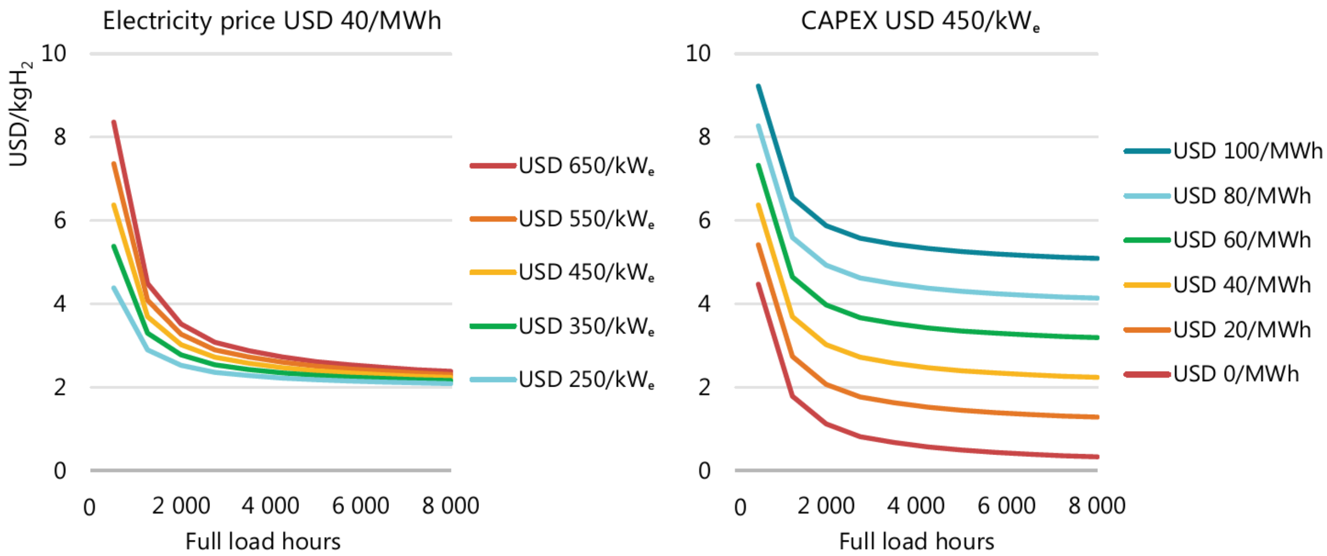


Figure 3: Future 15evelized cost of hydrogen production by operating hour for different electrolyser investment costs (left) and electricity costs (right)

Notes: MWh = megawatt hour. Based on an electrolyser efficiency of 69% lower heating value (LHV) and a discount rate of 8%.

Source: (IEA 2019, p 47).

A comparison of the lowest renewable energy production costs for different countries and technologies is provided in Figure 4. For Saudi Arabia, utility-scale PV systems represent the lowest electricity generation costs, but it should be considered that an energy mix – for example combined with wind power – will bring a steadier power generation.

On average, the total of annual sunny hours amounts to 3230 in Riyadh Province, representing 36.9% or more than one-third of total annual hours.

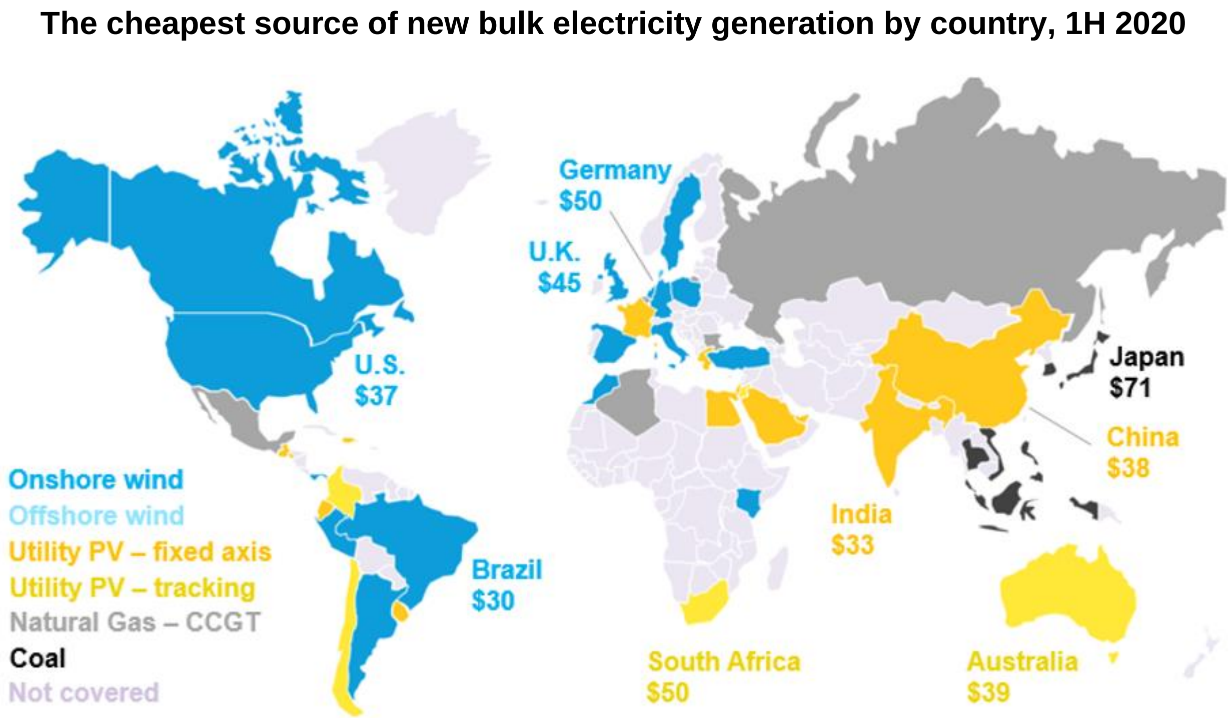


Figure 4: Cheapest source of new bulk electricity generation by country, 1H 2020

Source: (BloombergNEF 2020b)

Note: LCOE calculations exclude subsidies or tax credits. The graph shows the benchmark LCOE for each country in USD per megawatt-hour. CCGT: Combined-cycle gas turbine.

In Saudi Arabia, more than 2000 full load hours (FLh) can be achieved with single-axis tracking PV systems as indicated in Figure 5. This is about twice what can be yielded in Germany.

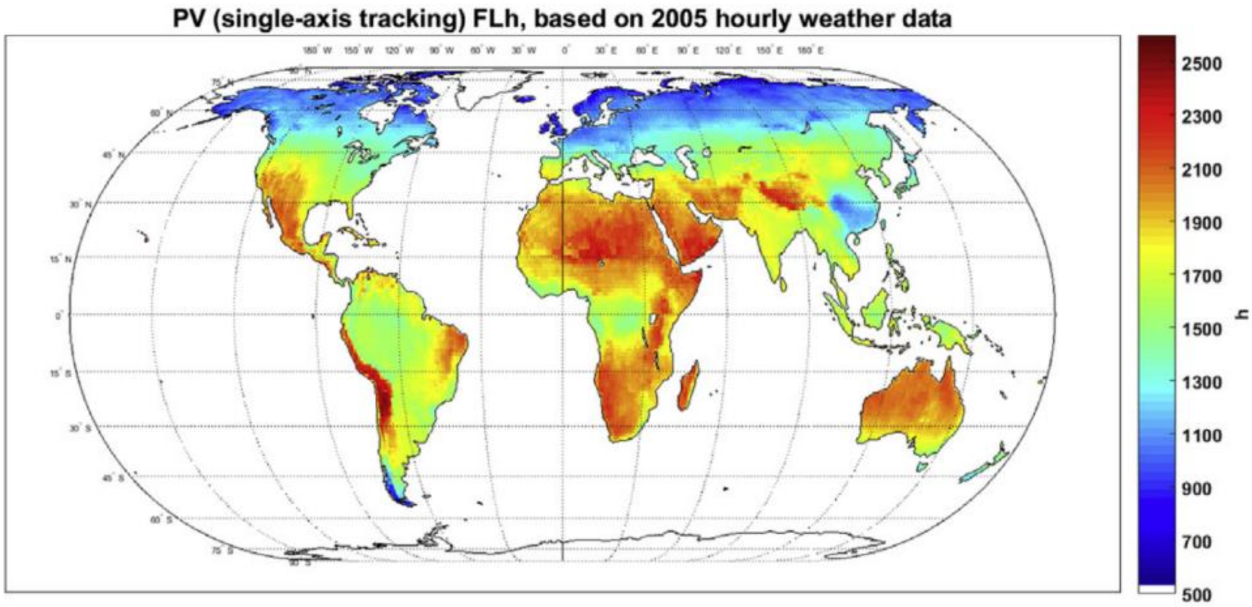


Figure 5: Full load hours per year for PV Systems with 1-axis tracking

Source: Fasihi, M & Breyer, C 2020, 'Baseload electricity and hydrogen supply based on hybrid PV-wind power plants', Journal of Cleaner Production, vol. 243, p. 118466.

1.1.2 Need for action – the environmental argument

Internationally, it is agreed upon that the basis of life on planet earth is massively endangered by climate change. The effects of climate change threaten life on earth – for example, by making it simply too hot to survive in some areas. In addition, extreme weather events can damage or destroy vital infrastructure. Due to climate change, the probability of extreme precipitation, droughts, or storms with very high wind speeds may increase many times over. This can affect existing conventional infrastructures as well as newly built renewable energy power plants.

There is a link between the ecologic and the economic arguments: extreme weather events may damage buildings and infrastructure and can be very costly. Insurance companies are aware of this development and insurance policies are becoming more expensive. Furthermore, crop failures can cause loss of earnings for farmers and jeopardize the food security.

Many scientists claim that the window of opportunity to mitigate this disastrous development is closing soon. Therefore, greenhouse gas emissions must be limited immediately. Key insights are provided in the latest reports of the Intergovernmental Panel on Climate Change IPCC.

1.1.3 Opportunity for Saudi Arabia

It is imperative to reduce CO_2 emissions at a global level and from an economic standpoint there are strong arguments to push renewable energies in order to remain competitive in a green future. The economic argument is that renewable energies, like solar and wind, are already today the least cost to generate electricity. New research led by Aarhus University in Denmark suggests that solar energy has the potential to meet global electricity needs using just 0.3% of the world's land area. The study emphasizes that land availability and raw material constraints are unlikely to hinder the ascendancy of photovoltaics in the global energy scenario (PV-Magazine 2023).

Changing familiar habits and a (still) functioning system is a challenge. Luckily there are very favorable conditions for solar PV and wind power in the MENA region, and particularly in Saudi Arabia. A race has started for who will be able to produce green hydrogen or its derivates at the lowest costs. The question raised is which country(ies) will be able to satisfy Asia’s or Europe´s large energy needs, regions that will further depend on imports of energy carriers in the long run without emitting CO_2?

Saudi Arabia presents strong credentials in such a race: the financial power to invest in a rapid expansion of renewable energies and the expressed political will making it a top priority.

Box 1: Carbon Capture

CCS or CCUS adds cost to the power generation and requires additional energy for extraction, treatment and compression of the carbon dioxide gas. For a typical coal-fired plant with post combustion capture, the net efficiency could be expected to drop by as much as 7 to 12% due to the heat and power requirements of the capture process. Compression of CO_2 is expected to consume 90-120 kWh of electrical power per ton of CO_2, contributing to additional losses of 30-50% of the total generated power (Jackson & Brodal 2018).

From the existing literature, we learn that lowest costs for CCS technologies are pre-combustion for coal-fired power plants and post-combustion for gas-fired power plants. LCOE rise from 5.4 to 6.9 $ct/kWh for pre-combustion CCS technology at coal-fired power plants, which is an increase of about 28%. Post-combustion CCS technology at gas-fired power plants increases LCOE from 6.2 to 8.0 $c/kWh, which is an increase by 29%. The thermal efficiency – expressed in percent of Lower Heating Value (LHV) – decreases by about 28% for coal- and about 15% for gas-fired power plants. It means that about 15 to 30% additional fuel is consumed in the electricity generation to capture the CO_2. Investment costs increase by 29% (coal, pre-combustion) to 74% (gas, post-combustion CCS process). Costs include CO_2 capture and compression to 110 bar (= 11 Mpa), but transportation and storage costs are excluded and come on top (IEA GHG 2006).

Carbon capture from natural gas with CCS is the cheapest technology in international comparison and is estimated to add about 50 US$/MWh (or 80 $/ton CO_2) in Saudi Arabia (GLOBAL CCS INSTITUTE 2017).

The studies mentioned, while not entirely recent, maintain relevance and should be considered in the present context. The losses mentioned above, as well as the additional investments and operating costs, are still likely to be valid, but will change in the future.

Also, the captured CO_2 could be used for enhanced oil recovery, which may lead to a different economic prospect.

1.2 Study objectives

The key objective of the study is formulated as follows: what is in for Saudi Arabia in terms of future hydrogen exports to its key off-taker markets? More precisely the central questions are: How seriously and swiftly will Saudi Arabia's main off-taker markets shift away from fossil fuels on their road to climate neutrality? And how much demand for green hydrogen (and its derivatives') imports will arise in these markets that Saudi Arabia could potentially cater to?

The main objective of the study is therefore to provide an outlook of Saudi Arabia's most important energy export markets from the perspective of climate neutrality, the reduction of CO_2 emissions, and the production and use of green hydrogen. As of today, the key off-taker markets are mainly divided between Asia and Europe. As such, these two regions are the only ones taken into consideration in this study.

Based on existing trade flows, questions raised and addressed in the study are:

- What and how much energy carriers (oil and oil products, ammonia and methanol) do Saudi Arabia's key off-taker markets currently import from the Kingdom and in which quantities, amounting to what sum, and for what industrial purpose(s)?

- What goals have Saudi Arabia's key off-taker markets set for themselves in terms of CO_2-emission reduction in general and in which timeframe; how do they intend to reach climate neutrality and through which key technologies and with the support of which energy sources?
- What will be the intended role of hydrogen in Saudi Arabia's key off-taker markets and to what extent will/could hydrogen as such replace oil and oil derivative products still being imported?
- According to Saudi Arabia's key off-taker markets' set ambitions for the use of green hydrogen and their domestic production forecasts, how does Saudi-Arabia's own announced hydrogen production (and use) could match with the upcoming demand in key Asian and European countries? And how competitive in terms of costs could Saudi hydrogen and derivates export be?

1.3 Report structure

The study is structured as follows:

Chapter 2 addresses **Saudi Arabia's key off-taker markets**.

Saudi Arabia's amounts and revenues from exporting energy carriers to Asia (China, India, Japan, South Korea) and Europe (Belgium, France, Germany, Netherlands, United Kingdom) as well as product prices are assessed. Volumes of oil and oil products, ammonia and methanol are investigated as well as the value traded and specific selling price. Also, it is shown for which applications which amounts of these energy carriers are used. The electricity generation mix is described for these off-taker countries and the role of fossil fuels for electricity generation. Finally, the primary energy consumption and existing trade agreements and relationships between the trade partners and Saudi Arabia are described.

Chapter 3 explores the **net-zero targets and hydrogen ambitions of Saudi-Arabia's main trading partners**.

For the selected key off-taker markets in Asia and Europe, their respective targets to produce and consume hydrogen and PtX are provided. The established renewable energy (RE) roadmaps are investigated, and the different sectors of energy usage listed. Key figures of the national hydrogen roadmap and its timetable are compiled. The derivation of current hydrogen demand based on imports of fossil fuels is presented, taking into account announced developments. The expected import demand for hydrogen and PtX and the most feasible trade routes (pipelines, shipping of liquified hydrogen, shipping of ammonia) are explored. The existing infrastructures for each country in these three trade routes are assessed. In some countries the demand for hydrogen and PtX cannot be satisfied by domestic production and the role of importing such goods is indicated.

Chapter 4 examines **Saudi Arabia's own hydrogen potential and announced ambitions in a changing energy landscape**.

In this chapter, Saudi Arabia's hydrogen potential is examined by highlighting the RE potential, existing and planned projects. The water resources available in Saudi Arabia as a main required source for green hydrogen production process via electrolysis is addressed. Hydrogen types and derivatives in relation to local industry shall also be investigated.

Concerning Saudi Arabia's energy usage for transportation purposes, hydrogen´s different forms are investigated in relation to the existing and planned infrastructures (grids, pipelines, etc.) and the way of hydrogen products´ export from Saudi Arabia to the off-takers countries.

Chapter 5 brings together the findings of the previous chapters and draws conclusions and recommendations for **Saudi Arabia's potential as a world energy provider** in light of the upcoming hydrogen economy.

In the Appendix a list of abbreviations and definitions is provided.

2 Assessment of Saudi Arabia's key off-taker markets

This first general chapter examines Saudi Arabia's main customer markets. The analysis provides historical trade volumes for the main exported energy sources, i.e. crude oil and petroleum-based products such as gasoline, diesel, kerosene and other refined products. Because of their current and, in particular, potential future importance, ammonia and methanol are also examined. In this way, the degree of trade dependence between the two sides, Saudi Arabia as a supplier and the consuming countries in Asia and Europe, becomes clear. The international product codes (HS) for the products studied are provided in Table 1.

Table 1: Product HS code for oil products, ammonia and methanol

Product HS code	Product description
2709	Petroleum oils and oils obtained from bituminous minerals, crude
2710	Petroleum oils and oils obtained from bituminous minerals (excluding crude)...
281410	Anhydrous ammonia
290511	Methanol, methyl alcohol

Source: Product code classification based on ITC TradeMap (https://www.trademap.org).

Note: Product 281420 "Ammonia in aqueous solution" were found to be traded in irrelevant amounts only.

The key off-taker market in Asia that will be focused on are: China (CN), India (IN), Japan (JP) and South Korea (KR).

The trading partners of Saudi Arabia in Europe which will be examined in more detail are: Belgium (BE), France (FR), Germany (DE), the Netherlands (NL) and the United Kingdom (UK).

Data availability: time series from 2002 until 2021 (depending on the product). Units: revenues in Mio. USD; volumes traded in Mio. tons; share of country's imports related to total Saudi Arabia's exported product; share of country's imports from Saudi Arabia to total world imports .

The relevance of mineral products (Section 5 in statistics terminology) with crude oil being the most relevant one for the foreign trade value is highlighted in Figure 6 for 2019. The pie chart depicts the next two most relevant following sections: "7-Plastics & rubber and articles thereof" as well as section "6-Products of the chemical or allied industries". For both sections methanol is relevant as a source material while ammonia is only relevant for section 6.

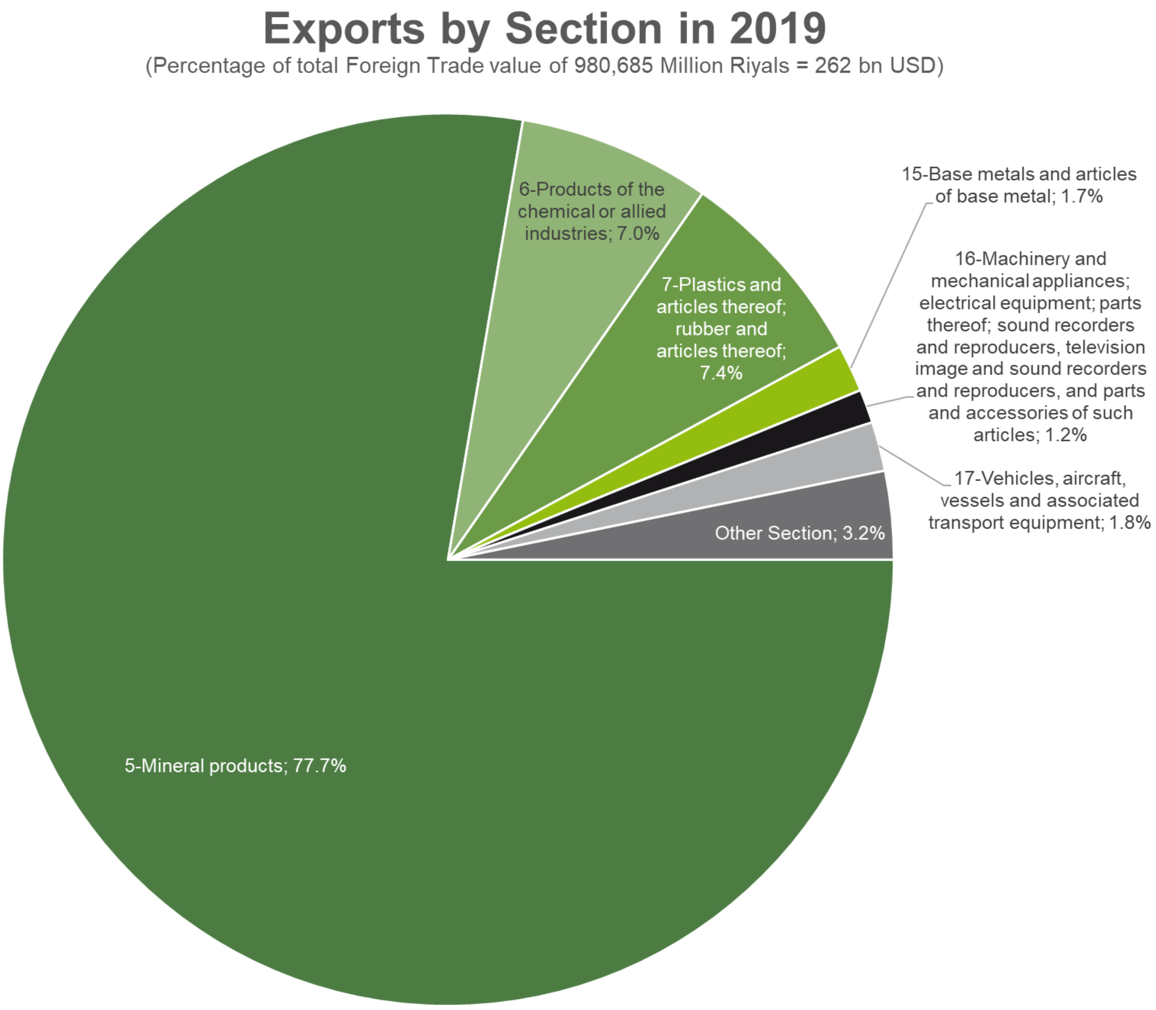


Figure 6: Saudi Arabia's Export by Section in 2019

Source: GASTAT, Table 7-2-1; Graph: PSE Projects

2.1 Saudi Arabia’s revenues and trade volumes from export of energy carriers to selected countries in Asia and Europe

Which role plays Saudi Arabia as a supplier for the selected regions compared to the total supply of crude oil and oil products?How much crude oil and oil products are sourced from Saudi Arabia compared to the total import of the selected regions?

The same questions are analyzed for ammonia and methanol in this section.

2.1.1 Crude oil and oil based products

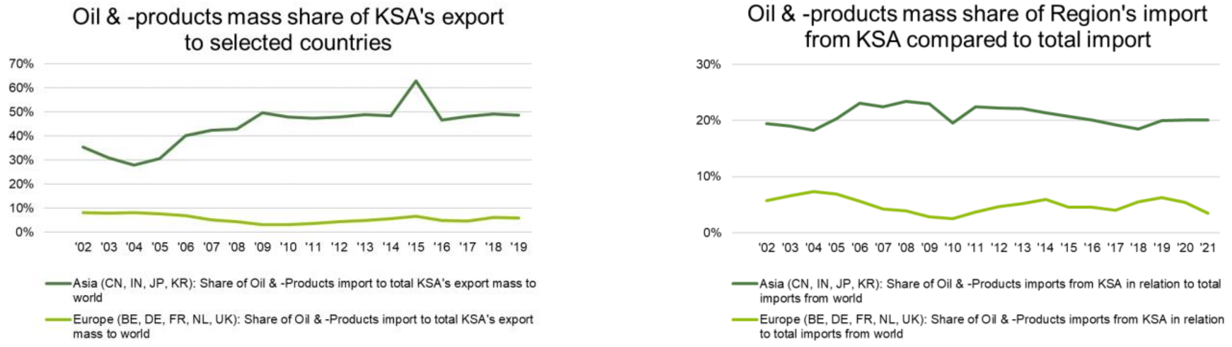


Figure 7: Relevance of Saudi Arabia as a supplier of oil and oil products to selected countries in Asia and Europe

Source: UN TradeMap, Data retrieved on 24.11.2022 (https://www.trademap.org/); Graph: PSE Projects

Key off-takers in Asia take about 43% of the oil and oil based product export mass (in metric tons) of Saudi Arabia (see Figure 7 left graph). The share of the selected off-taker markets in Europe contributed to about 6% of Saudi Arabia's exported mass as a mean value in the given period. To assess the market potential, the right graph in Figure 7 shows how much oil & -products are delivered from Saudi Arabia compared to the total imported amount. About 21% of crude oil and oil products imports to Asian key off-taker markets are sourced from Saudi Arabia; for Europe it is just about 4% as the average share from the last 20 years.

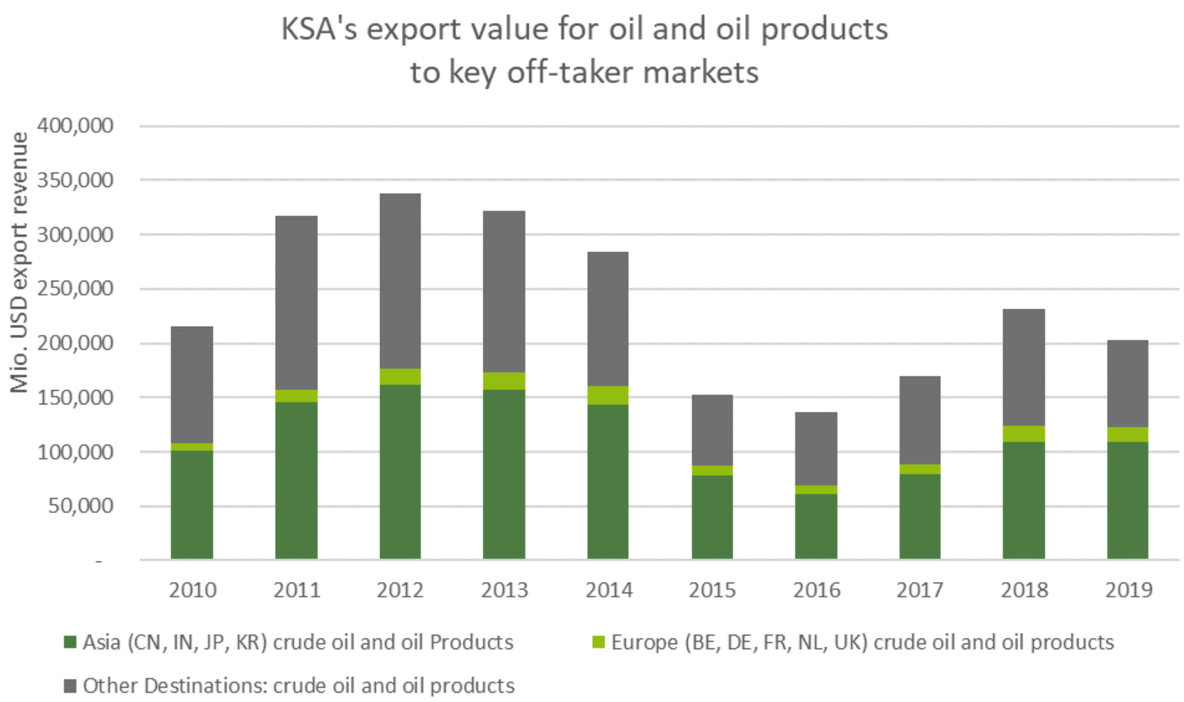


Figure 8: Saudi Arabia's export revenues for oil & oil products to key off-taker markets in Asia and Europe

Source: Total revenue: GASTAT; values for Asia and Europe: UN TradeMap; values for other destinations: calculated; Graph: PSE Projects

2.1.2 Ammonia

It is expected that ammonia (NH_3) will play a key role as an energy carrier for shipping. It is produced through the Haber-Bosch process and one of the main use of ammonia is the production of fertilizer for the agricultural sector. Global annual production amounts to 185 million tons of ammonia in 2020 (IEA 2021a, p 25). To produce ammonia, nitrogen and hydrogen are needed. In conventional production, hydrogen is generated by steam-methane reforming (SMR) of natural gas.

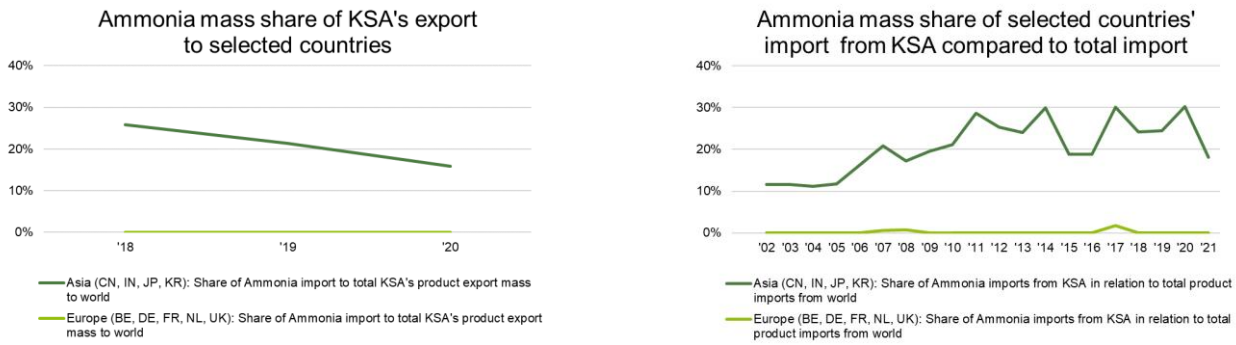


Figure 9: Relevance of Saudi Arabia as a supplier of ammonia to selected countries in Asia and Europe

Source: UN TradeMap, Data retrieved on 24.11.2022 (https://www.trademap.org/); Graph: PSE Projects

Note: Before 2012, no data for Ammonia trade are available on UN TradeMap. In some years, such as in 2017 there are inconstancies; for example, the total Saudi Arabia's exports are lower than the export to Asia, which does not make sense. This is why the left graph is only shown for the period from 2018 to 2020.

2.1.3 Methanol

Methanol (CH_3OH) is another interesting energy carrier and chemical precursor that is liquid at ambient temperatures and can easily be shipped. Methanol plays an important role as a feedstock for the chemical industry for the production of plastics, among other things. Every year, about 98 million tons (Mt) are produced worldwide, which up to now have almost exclusively been made from fossil fuels - natural gas or coal (IRENA and Methanol Institute 2021, p 4).

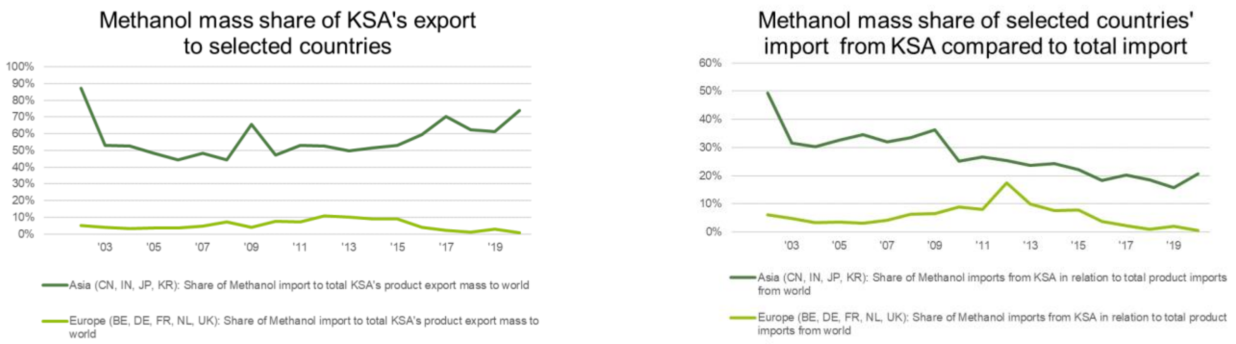


Figure 10: Relevance of Saudi Arabia as a supplier of methanol to selected countries in Asia and Europe

Source: UN TradeMap, Data retrieved on 24.11.2022 (https://www.trademap.org/); Graph: PSE Projects

Comparing methanol and ammonia in terms of export value Figure 11 shows that the export value of methanol to the Asian countries was highest. Second was ammonia export to the same region. Methanol exports to countries in Europe play a minor role and there was only a marginal export turnover from selling ammonia to this region.

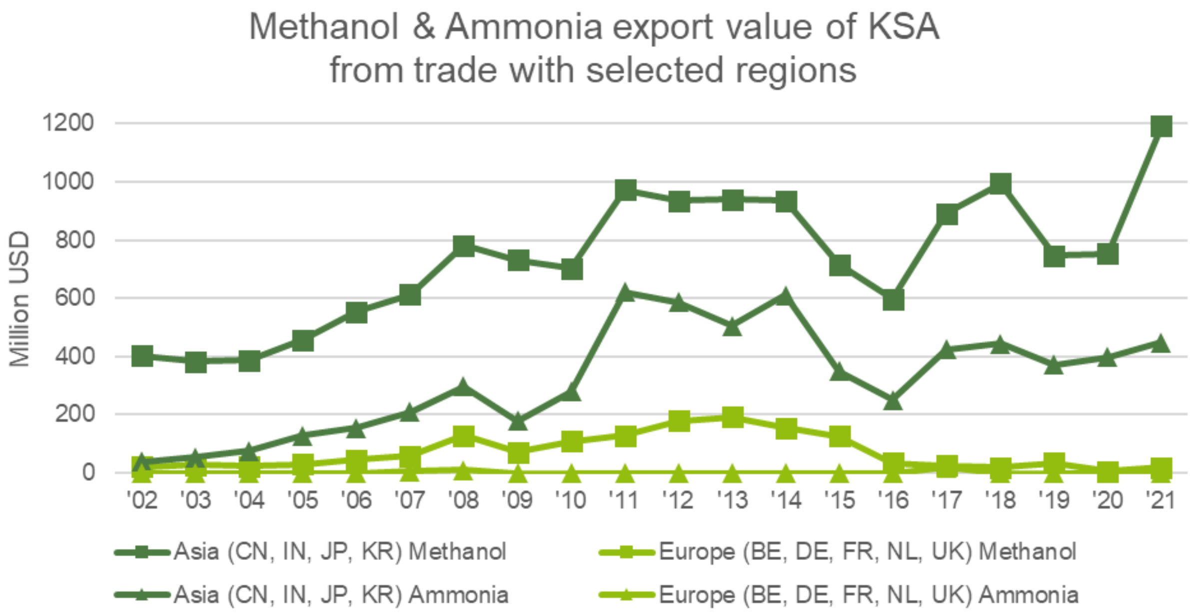


Figure 11: Turnover from Saudi Arabia's export of methanol and ammonia to selected regions

Source: UN TradeMap, Data retrieved on 24.11.2022 (https://www.trademap.org/); Graph: PSE Projects

Both methanol and ammonia are expected to become much more important as energy sources in the future. Especially in the European market, green manufactured products will play a significant role and will be in high demand. CCUS technologies can also be applied for the production of methanol (compare with Figure 57 on page 92 where carbon capture from conventional ammonia production is used in Jubail methanol production plant). With dwindling oil reserves, green or blue methanol or ammonia may become increasingly important as a feedstock for the chemical industry or as a future energy source (IEA 2023b).

2.2 Historical export prices

2.2.1 Historical development of crude oil price

Can higher revenues be achieved by exporting to Asia or Europe? Figure 12 demonstrates that over the last five years there has not been much difference: while higher prices tend to be obtained for oil products in European consumer markets, slightly higher prices are obtained for crude oil exports to Asia. As expected, higher prices and thus revenues are obtained through the export of oil products rather than through the trade in crude oil.

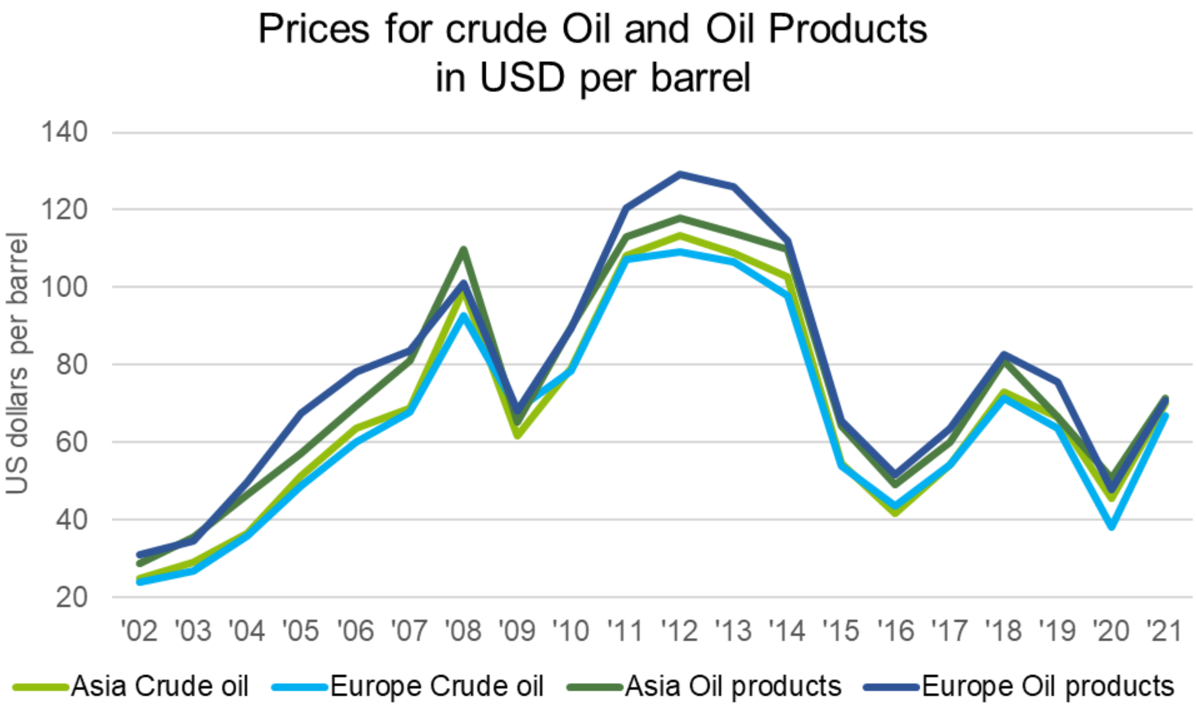


Figure 12: Export prices for crude oil and oil products by off-taker region

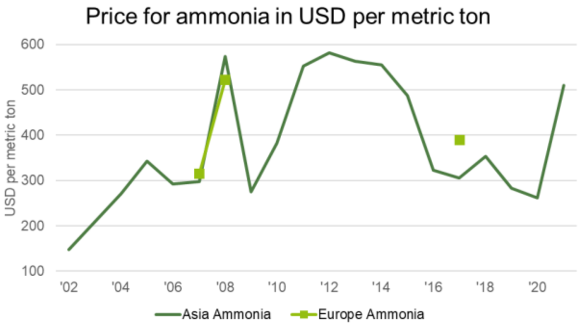
Source: UN TradeMap, Data retrieved on 24.11.2022 (https://www.trademap.org/); Graph: PSE Projects

Note: The values were calculated from turnover divided by mass applying the following conversion factors taken from bp Statistical Review of World Energy June 2022, Table
Approximate conversion factors: 7.33 Crude oil barrels to metric tons; 8.06 Oil product basket barrels to metric tons. (BP 2022)

$71.21/barrel was the mean price for oil and oil products in the period between 2002 and 2021. Expressed in USD per metric tons, the mean price for oil and oil products in the same period was $549.50/metric ton.

2.2.2 Price development of ammonia and methanol

The following price development of ammonia and methanol is based on UN TradeMap statistics. The mean value for ammonia shipped to the selected countries was $382.50/metric ton and for methanol, the mean price in the period between 2002 and 2021 was about $311/metric ton.



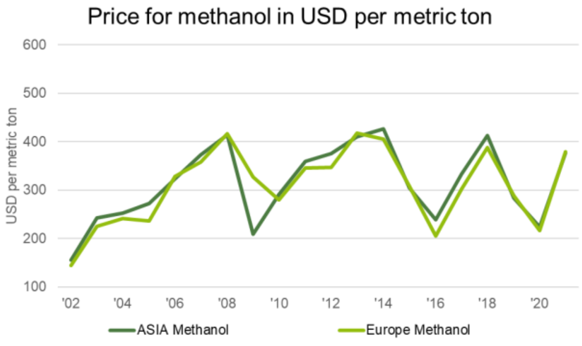


Figure 13: Price development for ammonia and methanol

Source: UN TradeMap, data retrieved on 24.11.2022 (https://www.trademap.org/) calculated from turnover divided by mass.

Note: For the trade price of ammonia to selected countries in Europe, the data was only partially available. That's why in the (left) graph only some price points could be displayed.

The prices of oil and oil products, ammonia and methanol have been volatile in the past. The price trends are interlinked and in principle follow the same pattern: when the price of oil peaked, the price of ammonia and methanol also peaked. Expressed in USD per ton as a mean value in the period 2002 to 2021, oil (Asia $495.86/ton; Europe $481.83/ton) and oil products (Asia $596.57/ton; Europe $623.72/ton) achieved the highest prices; followed by ammonia (Asia $378.52/ton; Europe $409.25/ton[2]) and methanol (Asia $313.85/ton; Europe $308.05/ton).

It can be expected that prices for products that are certified to have been produced without CO_2 emissions (so-called green products) will be higher than for products where CO_2 has been fully released (so-called grey products). The prices for blue products (that are those when CCS or CCUS has been applied) will depend on how credible and traceable the capture of the CO_2 has been carried out.

2.2.3 Today's and projected hydrogen price

In most regions the cost of low-emission hydrogen production was more expensive than the fossil fuels without the CCUS route in 2021 (IEA 2022b, p 92) as shown in Figure 14. The average cost comparisons are: $1.0-2.5/kg H_2 from unabated natural gas; $1.5-3.0/kg H_2 from natural gas with CCUS; and $4.0-9.0/kg H_2 for production via electrolysis with renewable electricity.

By 2030, hydrogen from solar PV could fall below $1.5/kg H_2 and by 2050 below $1/kg H_2 in regions with good solar conditions, (i.e. 2,600 full load hours), and thus low costs for electricity from solar PV, which account in these cases for around 55% of the total hydrogen production costs." (IEA 2022b, 93f). This is illustrated in Figure 14, where CO_2 emissions prices can have a strong impact on fossil fuel production prices (dashed areas in the diagram).

[2] Values for ammonia price in Europe are only available for the years 2007, 2008 and 2017

Opportunities for cost reductions to produce low-emission hydrogen

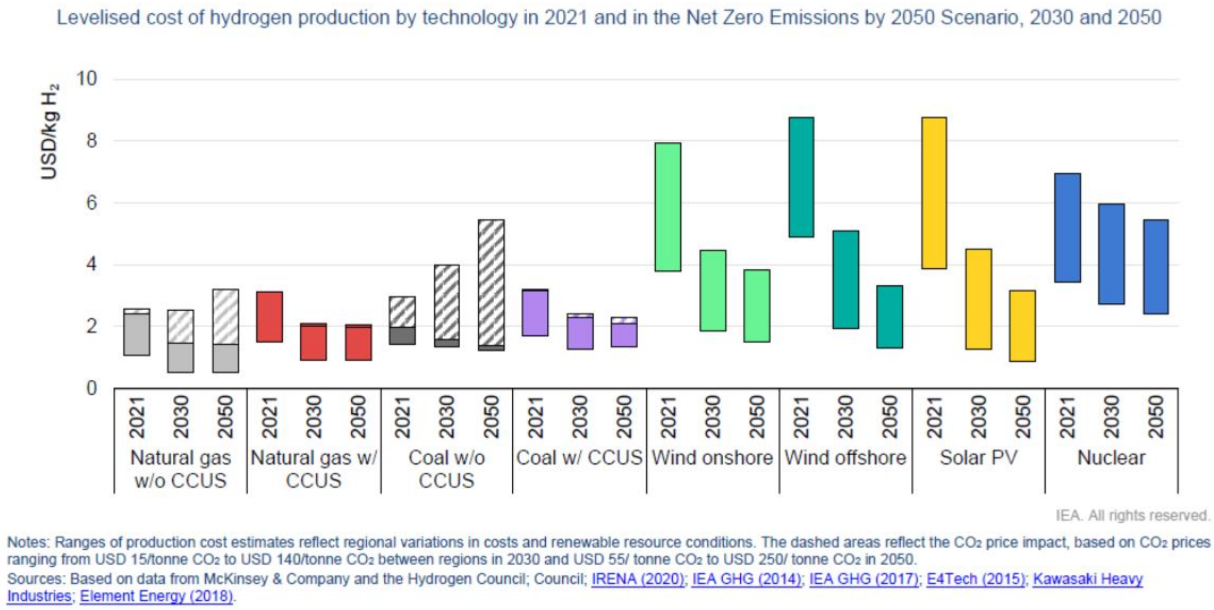


Figure 14: Opportunities for cost reductions to produce low-emission hydrogen

Source: (IEA 2022b, p 92)

Key cost components to generate green hydrogen are investment costs for electrolyser (CAPEX) and electrical power (as outlined in Figure 3 on page 15). Fresh water makes only a small share of the OPEX. With upscaling of the electrolyser production these costs will come down – similar to the learning curve of PV modules. Electrical power can be produced by wind and solar in Saudi Arabia very cheaply as outlined in chapter 1.1.1 on page 13.

2.3 Electricity generation mix in selected countries

2.3.1 Electricity from RE

The share of renewable energy is a good indicator of how far in the energy transition a country has proceeded. Also, this indicator provides an idea of how independent the country is from energy imports and about the future perspective to use additional renewable energy sources to produce green hydrogen. Figure 15 presents the total electricity generation in 2019 and the renewable energy shares in percent for the selected countries in Asia and Europe.

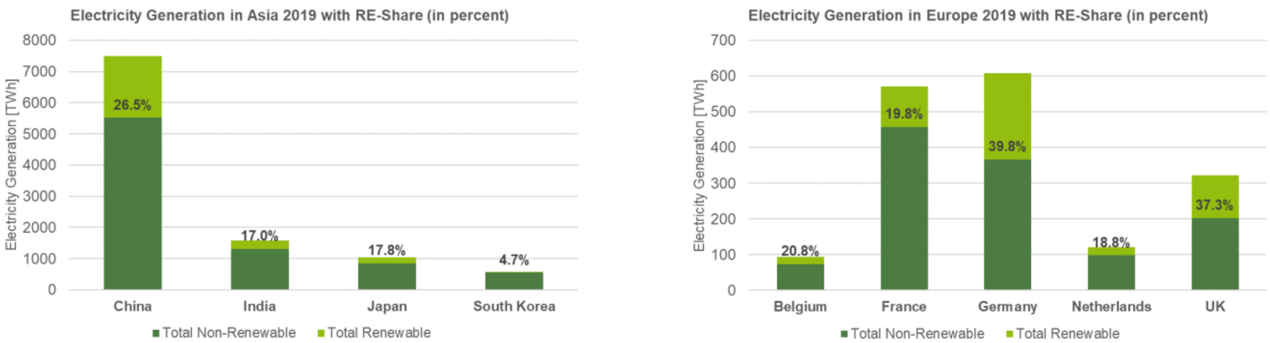


Figure 15: Electricity generation for selected countries in 2019 with the share of power produced by renewable energy systems

Source: (IRENA 2023a); Graph: PSE Projects

Note: Renewable energy systems include Hydropower (excl. Pumped Storage), Wind energy, Solar energy, Bioenergy, Geothermal energy, and Marine energy.

2.3.2 Role of hydrocarbons for electricity generation

Coal and natural gas are the dominating fossil fuels used for electricity generation in 2019. Figure 16 shows that electricity generation in India (75%), China (65%), South Korea (42%), Japan (32%) and Germany (30%) is strongly based on coal. Natural gas plays a significant role to produce electricity in the Netherlands (58%), the United Kingdom (40%), Japan (37%), Belgium (27%), South Korea (25%) and Germany (15%). Oil plays a minor role to generate power in the selected countries; Japan had the highest share with 3.5% of the electricity produced by oil as a fuel; South Korea's share of 1.6% and Netherlands 1.2%. All other countries were at or below 1%. Therefore, hydrogen or derivates could replace certain fossil fuels in the energy-intensive sectors of industry and power generation without displacing the current role of petroleum.

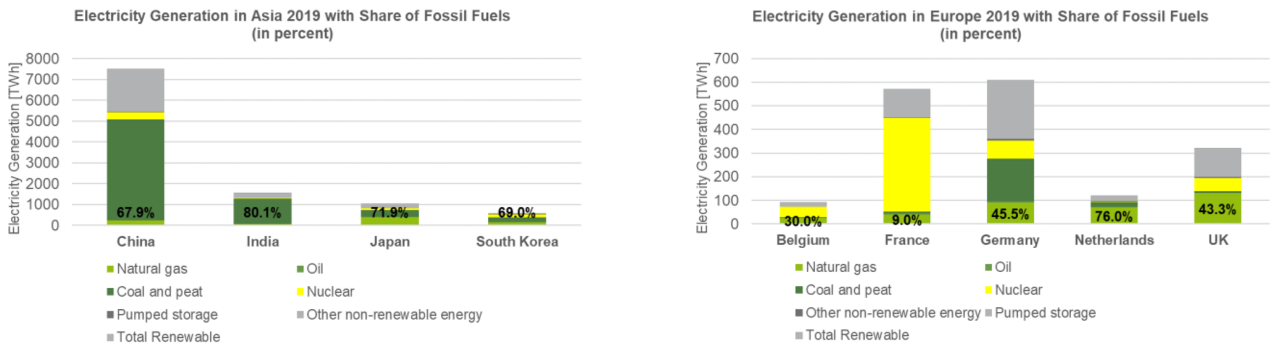


Figure 16: Electricity generation for selected countries in 2019 by source with shares of fossil fuels

Source: (IRENA 2023a); Graph: PSE Projects

Note: The scale of the Y-axis for the Asian countries is higher than for the European countries by a factor of 10. The percentage shown in the graph reflects the share of electricity generation from fossil fuels. It includes the use of natural gas, crude oil, coal and peat.

Countries whose electricity generation is largely based on coal and peat have the greatest pressure to replace this energy source with low- or zero-CO_2 electricity generation systems, as coal has the highest CO_2 emissions of all fossil fuels (WEForum 2020). As depicted in Figure 16, in 2019 a significant amount of electricity was generated by coal-fired power plants in China (4,850 TWh), India (1,200 TWh), Japan (329 TWh), South Korea (246 TWh) and Germany (182 TWh).

2.4 Primary energy consumption in selected countries

2.4.1 Fossil fuel demand and usage

Development of the total primary energy consumption in Asia with CAGR (2000-'21)

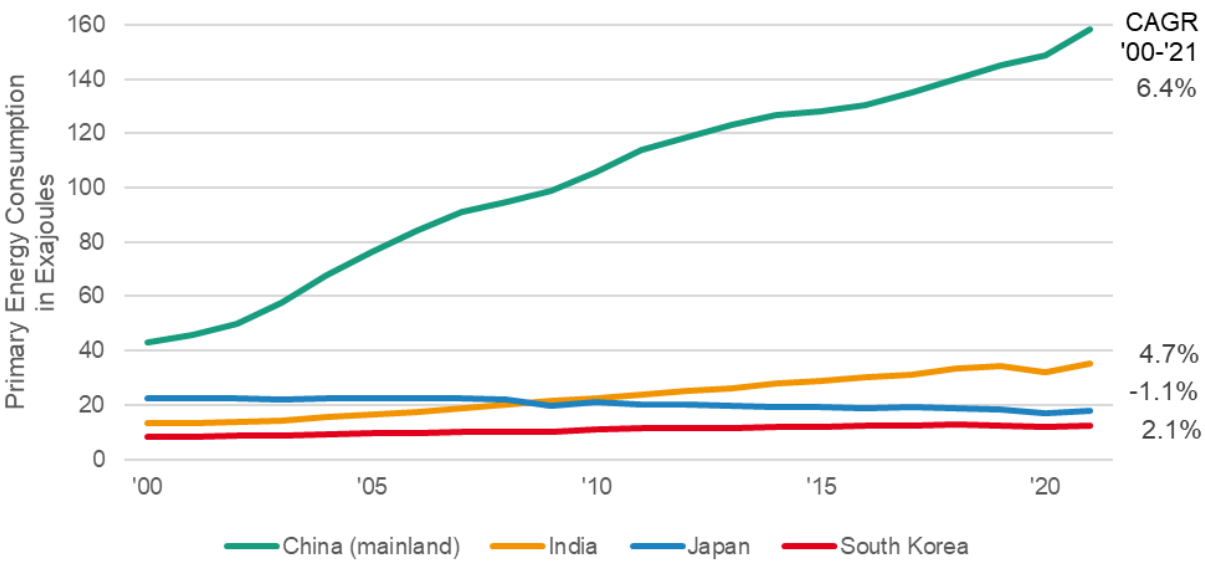
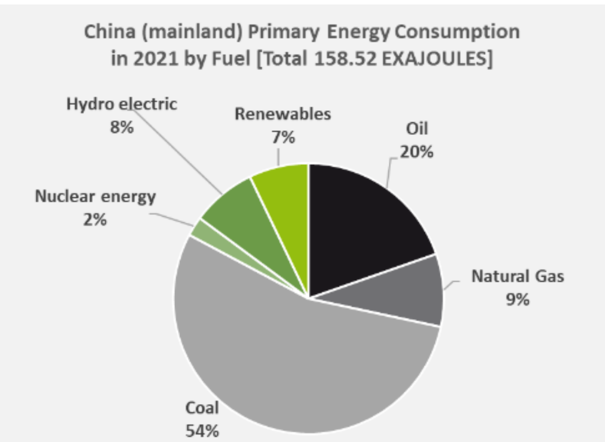


Figure 17: Total primary energy consumption development in selected countries in Asia

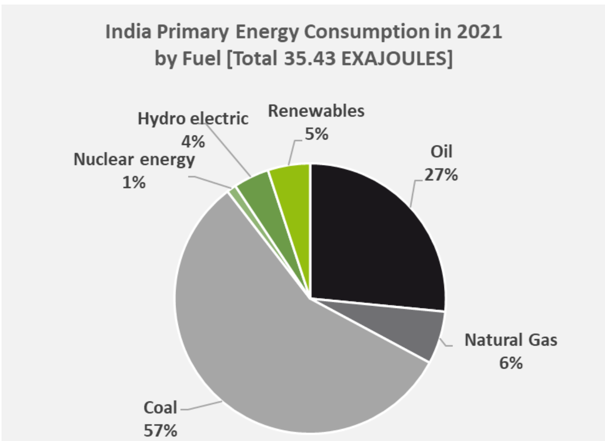
Source: bp Statistical Review of World Energy June 2022; Table 'Primary Energy Consumption'; Graph: PSE Projects

Today, China consumes 26.5% of the global primary energy and its primary energy demand grew most in all investigated countries with a compound average annual growth rate (CAGR) of +6.4% in the time frame between the years 2000 and 2021 (see Figure 17). Japan was the only analyzed Asian country with a negative CAGR for primary energy consumption (-1.1%), thanks to more efficient energy use.

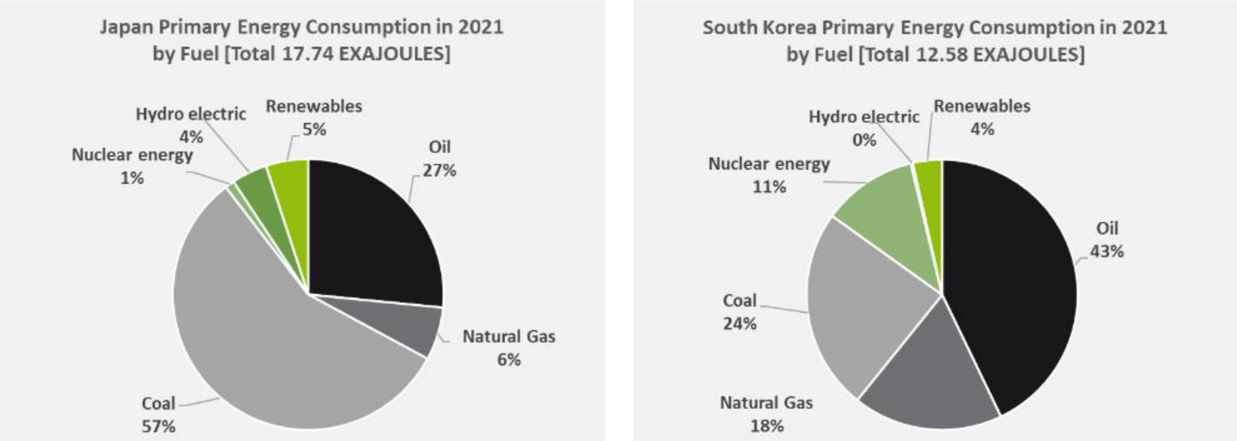
India officially surpassed demographically China by mid-2023 and it can be stated that on a per capita-basis, energy-consumption is still relatively low in India. As the population continues to grow, it can be expected that the annual increase in primary energy consumed will continue to rise as well.



158.52 EJ = 44,033.33 TWh calorific value



35.43 EJ = 9,841.67 TWh calorific value



17.74 EJ = 4,927.78 TWh calorific value   12.58 EJ = 3,494.44 TWh calorific value

Figure 18: Primary energy consumption in selected countries in Asia by fuel for the year 2021

Source: bp Statistical Review of World Energy June 2022; Table ‘Primary Energy - Cons by fuel’; Graph: PSE Projects

As depicted in Figure 18, primary energy consumption in India (57%), Japan (57%) and China (54%) are predominantly based on coal as a fuel to run thermal power stations and for heating purposes. In contrast, South Korea’s primary energy is mainly fueled by oil (43%) and coal (24%) plays a less significant role. South Korea’s usage of natural gas (18%) is the highest among the selected Asian countries.

Development of the total primary energy consumption in Europe with CAGR (2000-2021)

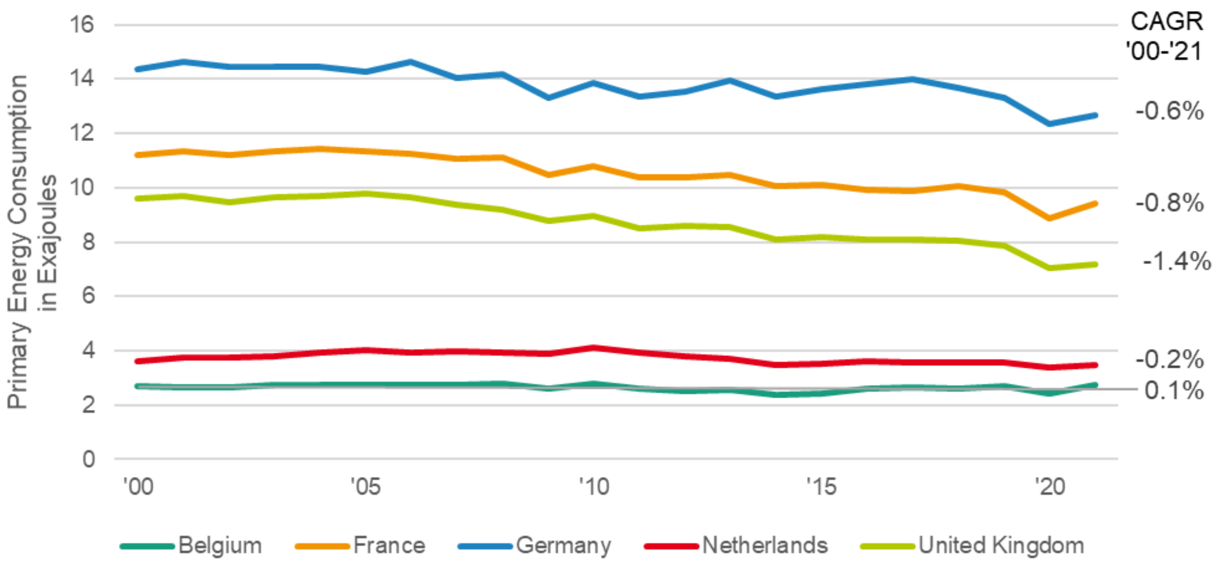
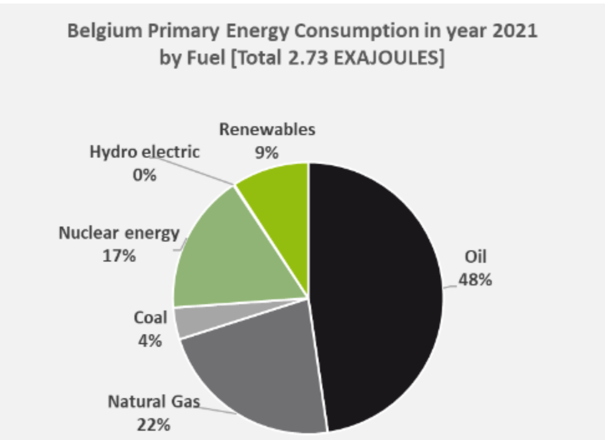


Figure 19: Total primary energy consumption development in selected countries in Europe

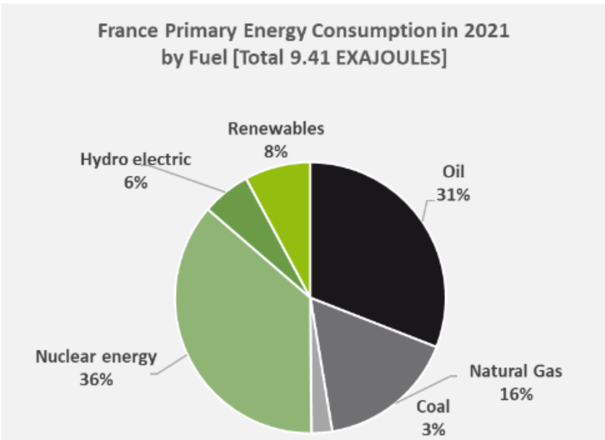
Source: bp Statistical Review of World Energy June 2022; Table 'Primary Energy Consumption'; Graph: PSE Projects

Figure 19 shows that with the exemption of Belgium, all European countries succeeded in reducing their primary energy consumption in the investigated period from 2000 to 2021. However, the slightly negative compound annual growth rate (CAGR) of total primary energy consumption in Europe is not as remarkable as one might expect, particularly in light of the ambitious goals that have been set and the recurring emphasis on tackling climate change.

Germany, France and United Kingdom show the highest primary energy consumption within the countries studied in Europe. As depicted in the pie charts in Figure 20, Germany has with 17% the highest share of coal consumption, but also with 18% the highest share in renewable energies. For comparison reason in the last pie chart, the global picture is provided.



2.73 EJ = 758.33 TWh calorific value



9.41 EJ = 2,613.89 TWh calorific value

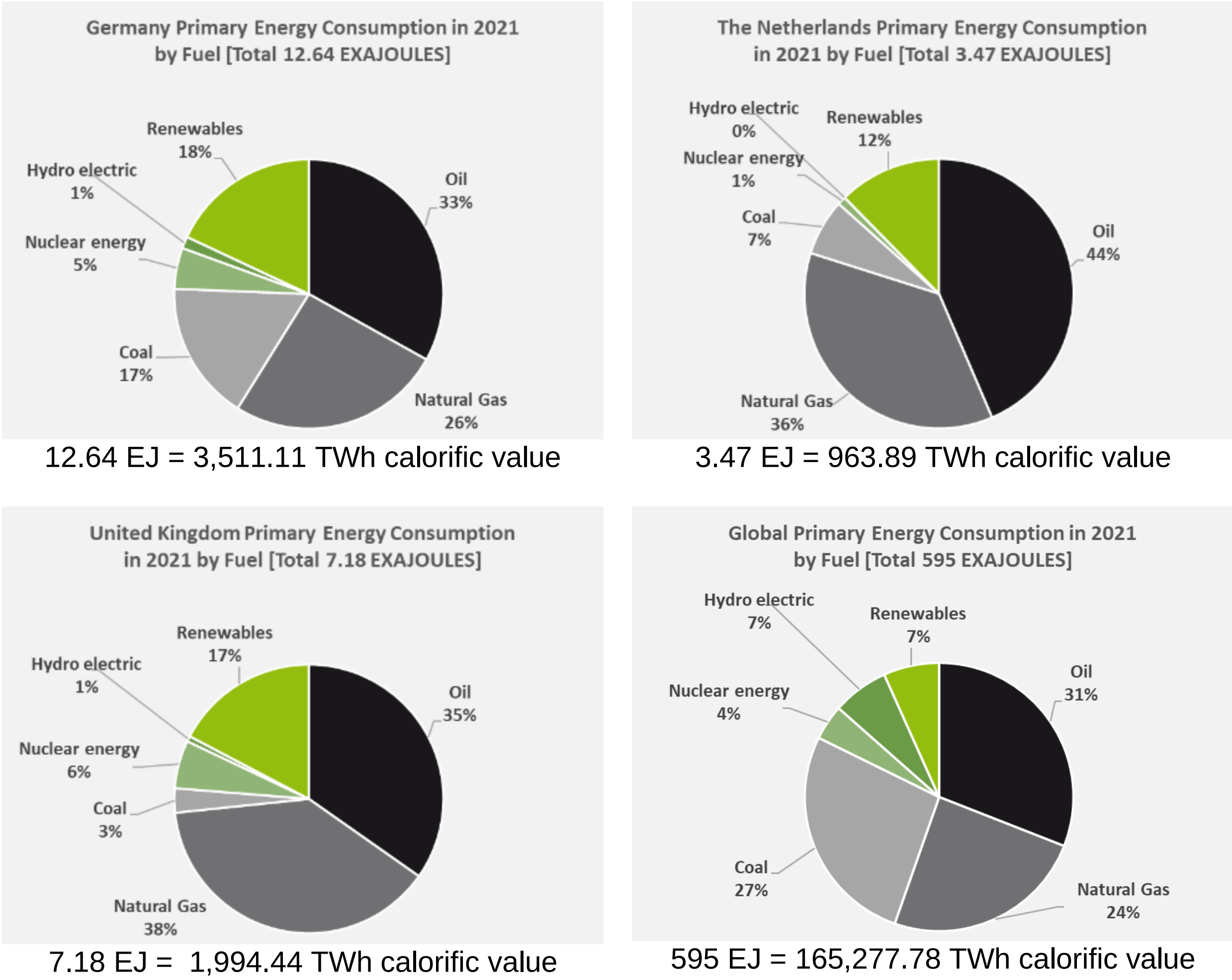


Figure 20: Primary energy consumption in selected countries in Europe and Global by fuel for the year 2021

Source: bp Statistical Review of World Energy June 2022; Table 'Primary Energy - Cons by fuel'; Graph: PSE Projects

What was oil used for in the past and today? Figure 21 provides the answer. Transport, including aviation, road, rail and (maritime) navigation plays a main role with 44.7% in total for 1973 and 65.3% for 2019. For rail, however, the rate decreased from 1.7% in 1973 to 0.8% in 2019 due to the electrification of railway lines. The trend to electrification in transport will continue – growing market shares of battery powered electric vehicles (BEV) are evidence of this development.

In general, the importance of oil in transport grew – quite significantly in road transport and aviation, while the role of oil in industry decreased over the past 46 years. It must be noticed that the non-energy use of oil increased from 11.6% in 1973 to 16.7% in 2019: its role in the chemical and pharmaceutical industry was getting stronger in the investigated period.

Until 2050, half of the total CO_2 abatement potential will come from transport according to IEA and Hydrogen Council (H2C 2017).

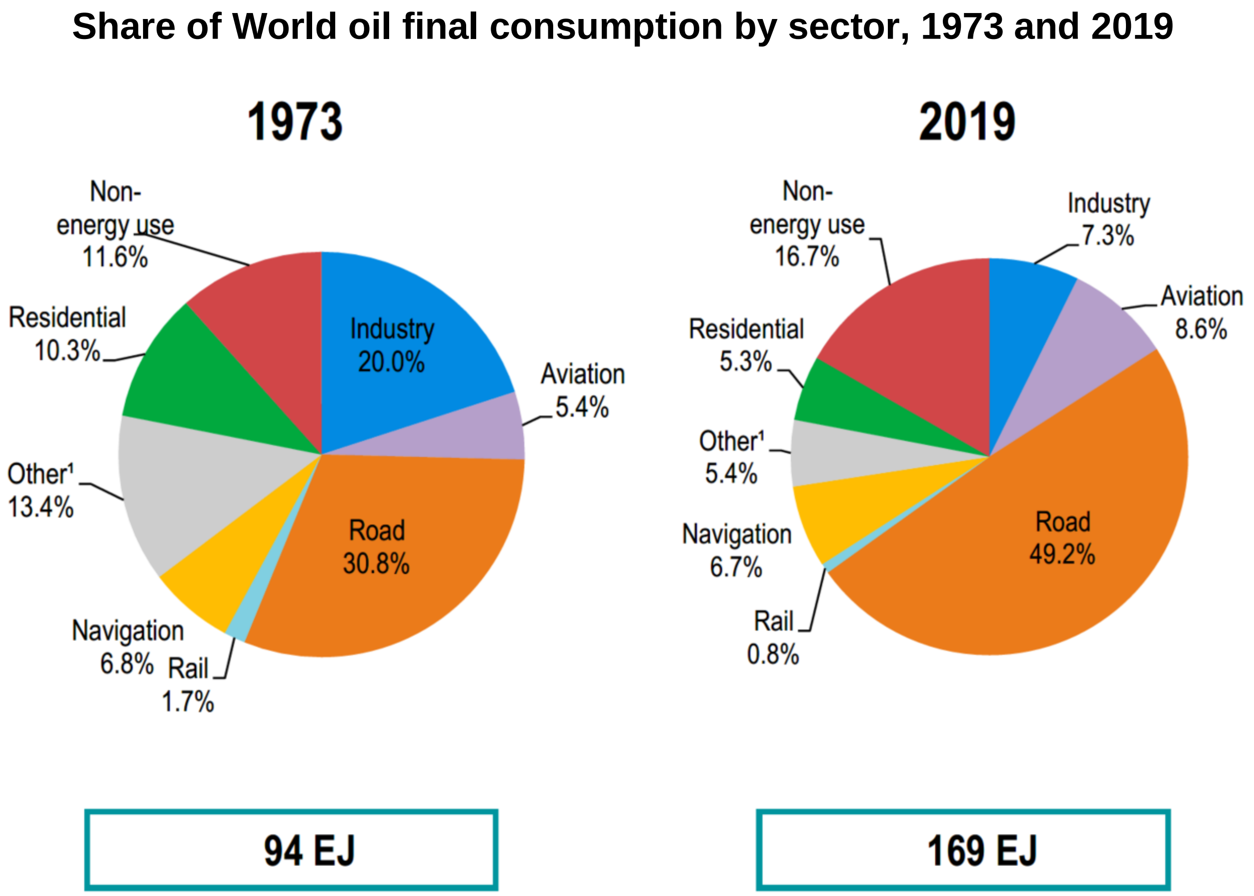


Figure 21: Oil final consumption by sector in percent, 1973 and 2019 compared

Note: [1]Includes agriculture, commercial and public services, non-specified other, pipeline and non-specified transport.
94 EJ = 26,111.11 TWh (1973) and 169 EJ = 46,944.44 TWh calorific value (2019).
Source: (IEA 2022d, p 39)

The oil consumption grew from 94 EJ in year 1973 to 169 EJ in 2019, which corresponds to a CAGR of 1.28%. Considering the almost doubling of the final oil consumption in the respective period, the residential sector using oil for heating and domestic hot water barely decreased with a CAGR of -0.17% from about 9.7 EJ (= 2,694 TWh calorific value) in 1973 to about 9.0 EJ (= 2,500 TWh calorific value) in 2019. Natural gas boiler, electrical heat pumps, solar thermal systems or wooden pellet burners have been replacing the oil heating systems in many industrialized countries.

Countries like Saudi Arabia are projected to broaden the application of oil in underexplored sectors like construction materials, as well as increase the usage of hydrocarbons for non-combustion purposes, such as plastics. Although the environmental impact of plastics is concerning, the CO_2 is stored within the material instead of being released into the atmosphere. Thus, the primary challenge lies in improving recycling technologies and methodologies, rather than the use of plastics themselves.

Important trends over the same 46-year period can be seen in Figure 22, which shows total global final consumption by source: **the use of electricity and natural gas increased, while the share of coal and oil decreased to some extent.**

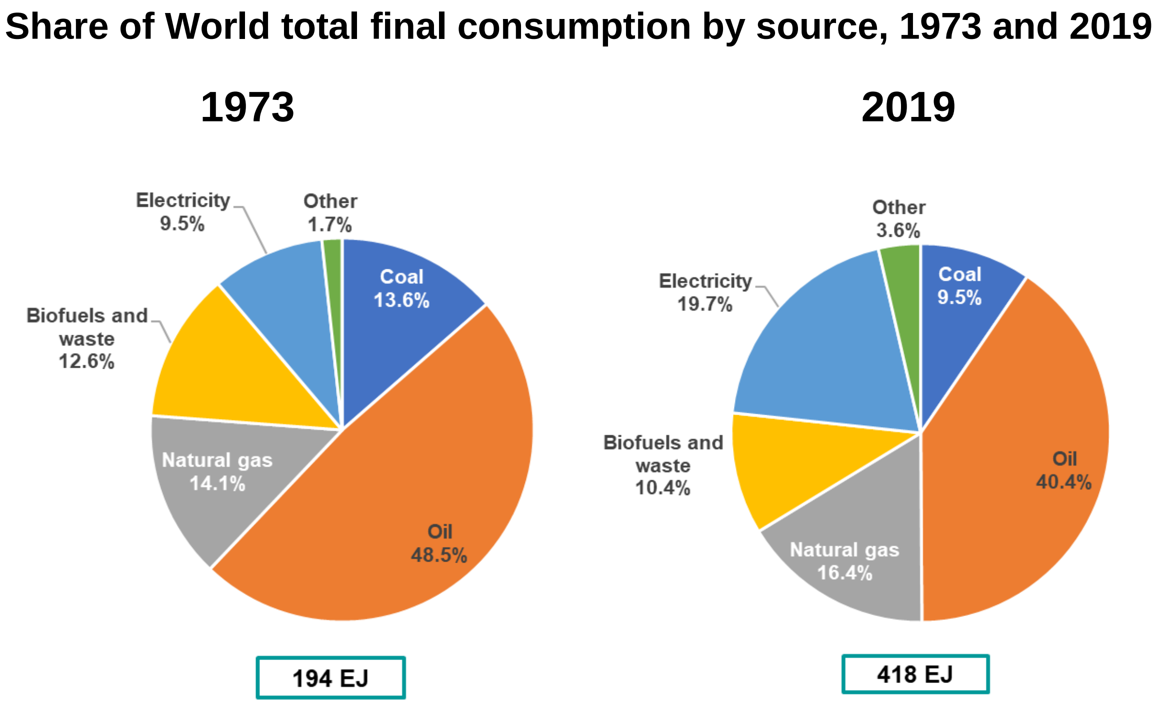


Figure 22: Share of world total final consumption by source, 1973 and 2019

Source: (IEA 2022d, p 34) Graph: Authors

Note: 1. World includes international aviation and international marine bunkers.
2. In these graphs, peat and oil shale are aggregated with coal.
3. Data for biofuels and waste final consumption have been estimated for a number of countries.
4. Includes heat, solar thermal and geothermal.

2.4.2 Hydrogen and PtX demand and usage

In 2021, 94 million tons (Mt) of the world's hydrogen demand was met primarily by hydrogen from fossil fuels. 62% was produced by natural gas reforming plants without CO_2 capture, while 19% came from unabated coal plants, mainly in China. The rest was generated as a by-product in facilities like refineries. This reliance on fossil fuels resulted in over 900 Mt of direct CO_2 emissions in 2020, accounting for 2.5% of global CO_2 emissions in energy and industry (IEA 2023b, p 39).

The key usages of hydrogen can be found in Figure 23: In the petrochemical industry, large quantities of hydrogen are used in the "upgrading" of fossil fuels. Key consumers of hydrogen include hydrodealkylation, desulphurization (= removing sulfur from hydrocarbons), and hydrocracking. Many of these reactions can be classified as hydrogenolysis, i.e., the cleavage of bonds to carbon.

Hydrogenation, the addition of hydrogen to various substrates, is conducted on a large scale. For example, the hydrogenation of nitrogen to produce ammonia through the Haber–Bosch process consumes around 2% (8.6 EJ) of total final energy consumption (IEA 2021a).

Methanol is produced by hydrogenation of carbon dioxide. Hydrogen is also used as a reducing agent for the conversion of some ores to metals (Borisut & Nuchitprasittichai 2019).

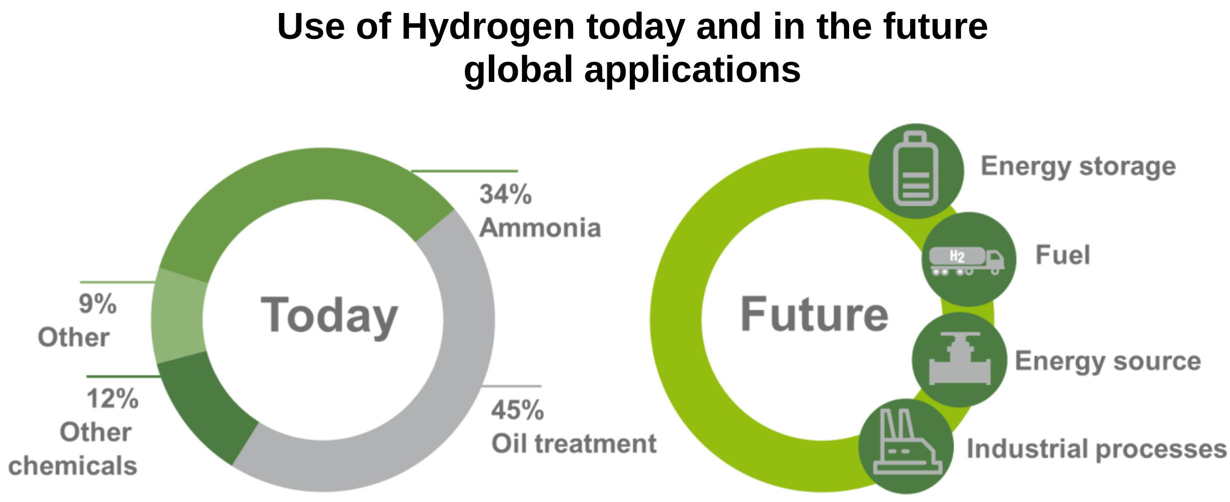


Figure 23: Use of hydrogen today and in the future - global applications

Source: (IKEM 2021)

A hydrogen demand forecast until 2050 is provided in Figure 25: The projected peak in demand for fossil fuels continues to move forward; demand for oil is projected to peak in the next five years (McKinsey 2022b). After this peak, refining in the petro-chemical industry will decrease as one of today's key applications while usage in industry e.g. for the production of plastics or other chemicals or the refinement of steel will definitely increase. Hydrogen can be used in fuel cells and South Korea and Japan are targeting such applications and developing infrastructures for transportation and to stabilize the grid in times when there is low yield from renewables. In addition, hydrogen can be mixed to some degree with natural gas and used as an energy source for home heating and water heating.

Hydrogen is essential for achieving climate neutrality and becomes unavoidable when reaching 80% GHG reductions compared to 1990. It will be an important, but not dominant, energy carrier in the future providing on average 4-11% of the final energy consumption in 2050. Its relevance will vary across regions and sectors. The transport sector has the highest hydrogen demand shares with the most uncertainty across all regions, followed by industry with higher certainty, especially in China. The building sector has the least hydrogen application potential and the highest projection certainty. Hydrogen demand varies significantly among regions, with the EU27 having the widest range of demand shares. However, the high uncertainty in hydrogen demand projections hinders investments in production, transport, and industrial usage, as hydrogen competes with other energy sources and relies on national climate ambitions and existing infrastructures (Riemer et al. 2022, 91f).

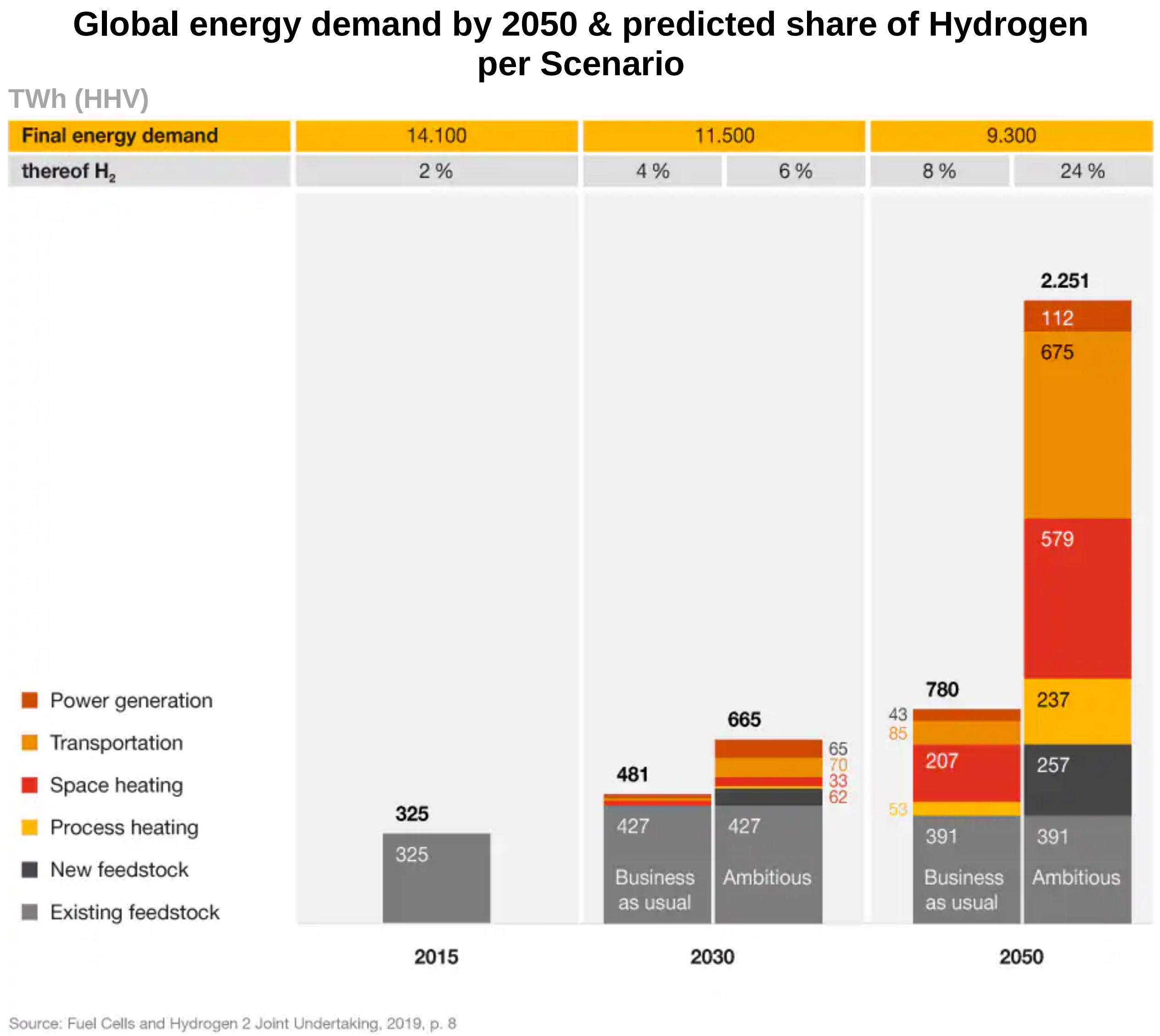


Figure 24: Global energy demand by 2050 and predicted share of Hydrogen in BAU and Ambitious Scenarios

Source: (PwC 2023)

Note: BAU means “business as usual”

Existing feedstock will increase until 2030 and after this peak it will decrease in both scenarios as depicted in Figure 24. Space heating is shown in the graph as very relevant. However, if a building is connected to the public power grid, then the use of hydrogen for heating buildings makes little sense, because heat pumps are much more efficient. For sure transport will play a significant role and at least Japan and South Korea strongly develop fuel cell powered electric vehicles (FCEL). New feedstock like green ammonia or methanol will play a strong role in the Ambitious Scenario. Power generation can also play an important role in a future with hydrogen. These are trends that are emerging. However, a precise prediction is not possible at the present time.

The high level of uncertainty is also expressed in Figure 25 in dependence on the achievements to limit global warming. The most ambitious scenario (less than 1.8°C global warming compared to 1990) suggests a global hydrogen demand of about 600 million tons in 2050.

Range of Hydrogen demand assessment by 2050

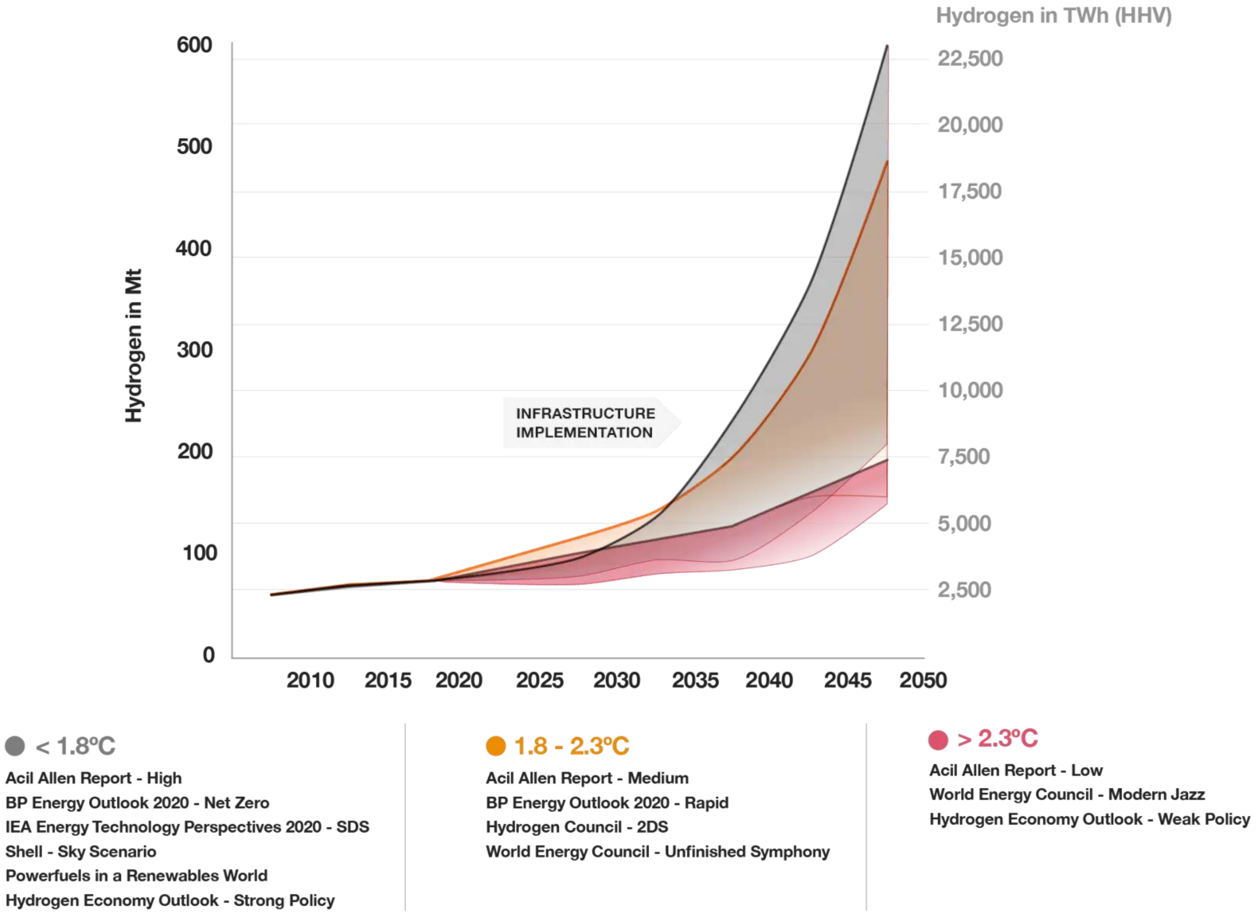


Figure 25: Range of Hydrogen demand assessment by 2050

Source: (PwC 2022)

Box 2: Food for thought experiment

Imagine all primary energy consumed from oil, natural gas or coal would be provided as hydrogen. Which amount of hydrogen would be needed in this case for each of the selected countries?

1 EJ is provided by 7 million tons or 78 billion cubic meters of gaseous hydrogen. It is equivalent to 990 billion British thermal units, 278 TWh of electricity, and roughly 170 million barrels of oil or 290 billion cubic feet of natural gas.
The energy content of 1 kg hydrogen:
141.9 MJ (HHV) = 39.4 kWh
120.1 MJ (LHV) = 33.3 kWh
The higher heating value (HHV) considers the latent heat of the vaporization of water in the combustion products, while the lower heating value (LHV) does not.
Source: National Academies of Sciences, Engineering, and Medicine. 2004. The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs. Washington, DC: The National Academies Press. https://doi.org/10.17226/10922.

The answer is provided in the following Table 2. Without considering efficiency gains from electrification and the use of hydrogen the second column from the right would be the result, which defines the maximum amount of hydrogen needed. However, there will be significant efficiency gains; for example a heat pump has a Coefficient of Performance (COP) of 3 to 4; instead of power generation by steam turbines with low efficiency, direct electricity generation by renewables takes place and an electric car needs about one-third of the primary energy (around 20 kWh per 100 km distance which would correspond to 2 liters of petrol) compared to cars consuming petrol or diesel.

As a rough estimate, we assume that only one-third of the energy will be consumed because of efficiency gains and these calculation results can be found in the right column. However, if in a future energy system the hydrogen would just be needed for combustion purposes, there would be (almost) no efficiency gains; hydrogen would just replace natural gas. We consider these amounts shown in the very right column therefore to be the minimum amount of hydrogen needed if the energy transition would have happened.

Table 2: Primary energy consumption of selected countries in 2021 converted in hydrogen mass as a thought experiment

Primary Energy: Consumption by fuel in year 2021	Oil	Natural Gas	Coal	Nuclear energy	Renewables incl. hydro electric	Total	RE share related to Total	Fossil fuel based*	Million tons H_2	Million tons H_2 with 66% reduction (efficiency gains)
	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]	[EJ]	[%]	[EJ]	[Mt H_2]	[Mt H_2]
Belgium	1.30	0.61	0.10	0.46	0.25	**2.73**	9.3%	2.0	14.1	4.7
France	2.91	1.55	0.23	3.43	1.29	**9.41**	13.7%	4.7	32.8	10.9
Germany	4.18	3.26	2.12	0.62	2.46	**12.64**	19.5%	10.2	71.3	23.8
Netherlands	1.51	1.26	0.23	0.03	0.43	**3.47**	12.4%	3.0	21.1	7.0
United Kingdom	2.50	2.77	0.21	0.41	1.29	**7.18**	17.9%	5.5	38.3	12.8
Saudi Arabia	6.59	4.22	^	-	0.01	**10.82**	0.1%	10.8	75.7	25.2
China (mainland incl. Hong Kong)	31.15	13.81	86.32	3.68	23.56	**158.52**	14.9%	131.3	918.9	306.3
India	9.41	2.24	20.09	0.40	3.30	**35.43**	9.3%	31.7	222.1	74.0
Japan	6.61	3.73	4.80	0.55	2.05	**17.74**	11.5%	15.1	106.0	35.3
South Korea	5.39	2.25	3.04	1.43	0.47	**12.58**	3.7%	10.7	74.8	24.9
Total World	**184.21**	**145.35**	**160.10**	**25.31**	**80.17**	**595.15**	**13.5%**	**489.67**	**3427.66**	**1142.55**

(Source: BP energy statistics 2022, 'Primary Energy: Consumption by fuel')
Note: Because Germany phased out from nuclear power, the amount from this source has been added here.

What can be learnt from this exercise?

It is difficult to imagine energy units like "millions of tons of hydrogen". With this thought experiment, one can better understand how to estimate the ratios. Europe, for example, has announced that it will import 10 Mt of hydrogen in 2030 and produce the same amount within its borders. It is clear that this is still not enough to meet the energy needs of the selected countries in Europe, which would require a minimum of 59.2 and a maximum of 177.6 million tons of hydrogen. To produce 1 Mt of hydrogen with continuous year-round operation, about 6 GW of electrolyser capacity must be installed, and typically 50 TWh of renewable electricity per year is required. The electricity requirement depends on the efficiency of the electrolyser. In Saudi Arabia, with its excellent solar conditions, about 20 GW of PV systems would be sufficient to generate the amount of electrical energy needed to produce 1 million tons of hydrogen per year.

The sources for hydrogen production and the application in demand are depicted in Figure 26. Supply by fossil fuels (mainly natural gas applying steam methane reformation SMR) is the predominant route today with a share of 99%. Water electrolysis – if performed with electrical energy from renewable energies called green hydrogen – is the path that has the potential to displace SMR. And the third option to produce hydrogen is bioenergy. Biohydrogen is generated through SMR of biomethane, fermentation, microbial fuel cells and production of biohydrogen by algae Researchers focus on enhancing biohydrogen yields using different bacteria strains and innovative techniques. Algae, such as Chlamydomonas reinhardtii, can also produce hydrogen in anaerobic conditions, with ongoing research to improve yields (ETIP Bioenergy 2023), further information (Xu, Zhou & Yu 2022).

Global Supply and Demand for low-emission hydrogen in the IEA net zero emissions scenario

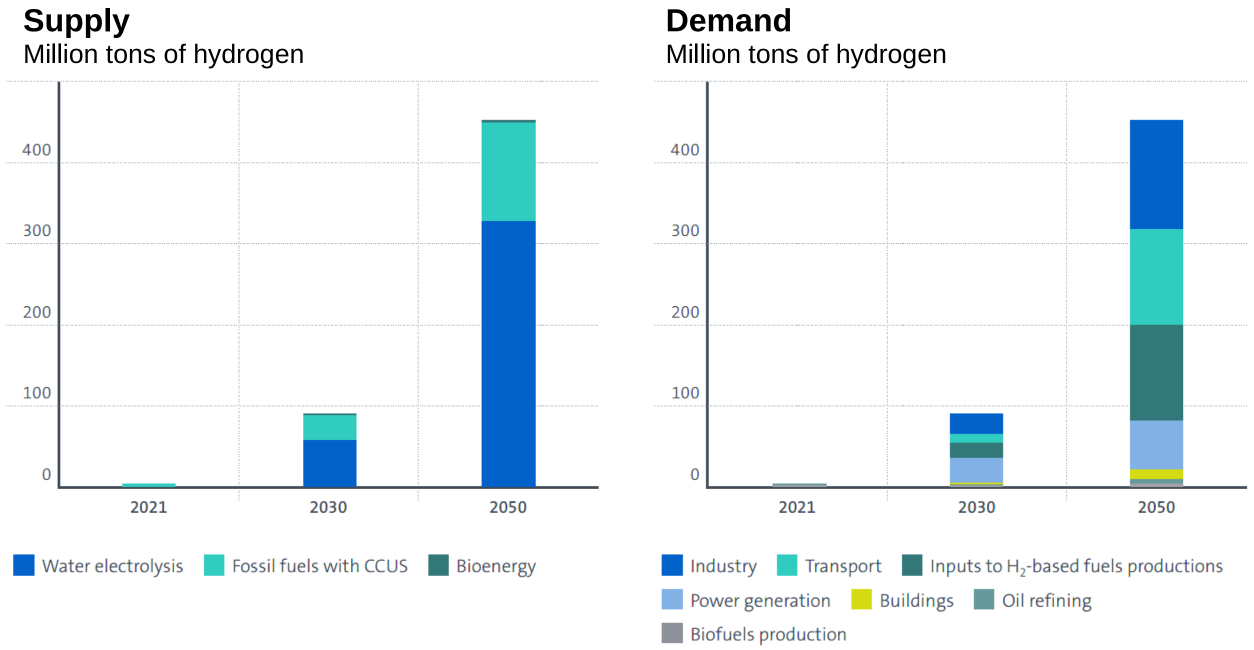


Figure 26: Supply and demand for low-emission hydrogen in the IEA net zero emissions scenario

Source: (IEA 2023b, p 21)

2.5 Overview of existing trade agreements between Saudi-Arabia and its key trade partners

Saudi Arabia is a member of the Gulf Cooperation Council (GCC) which consists of Kuwait, Qatar, Bahrain, the UAE, Oman, and Saudi Arabia. Saudi Arabia is also a member of the League of Arab States. The League has agreed to negotiate an Arab Free Trade Zone (ITA 2022).

No Free Trade Agreements (FTA) could be found between Saudi Arabia and the investigated countries. There are several FTA between the GCC and Arab countries and only one to European Free Trade Association (EFTA) countries which are Iceland, Liechtenstein, Norway and the Swiss Confederation. However, Trade and Investment Framework Agreement (TIFA) with Saudi Arabia are established with several countries. TIFA is typically an umbrella agreement for ongoing structured dialogue between trade partner governments on economic reforms and trade liberalization. The agreement promotes the establishment of legal protections for investors, improvements in intellectual property protection, more transparent and efficient customs procedures, and greater transparency in government and commercial regulations. (ibid.).

Trade Relationships with Asia

CHINA

YASREF refinery is a joint venture between Saudi Aramco and China Petrochemical Corporation (Sinopec) and a long-lasting collaboration exits between the two countries.

In December 2022, China and Saudi Arabia signed a strategic partnership during President Xi's visit to Saudi Arabia (NYtimes 2022), strengthening their economic, oil, and political ties. Saudi Arabia is China's top oil supplier, providing 18% of its crude oil purchases. Chinese oil demand is predicted to peak at 780 million tons per year before 2030 and decrease by more than half by 2050.

During the Sino-Saudi summit, 34 investment agreements were signed, covering green energy, information technology, cloud services, transportation, logistics, medical industries, housing, and construction (Reuters 2022). The leaders also pledged to enhance cooperation in hydrogen and other renewable energy sources. The Saudi Shoura Council approved a draft agreement between the Saudi Ministry of Energy and China's National Energy Administration concerning clean hydrogen energy.

Both Saudi Arabia and China face challenges in achieving their near-term green hydrogen production targets, including the fact that producing green hydrogen depends economically upon low renewable electricity costs. At a cost ranging from US$5.50-9.50/kilogram (kg), green hydrogen is currently considered the most expensive form of hydrogen to produce.

INDIA

India and Saudi Arabia have tied trade relations and bilateral agreements exist. For example the " Riyadh Declaration - A New Era of Strategic Partnership" was signed on February 28, 2010 and the following statement was signed on October 29, 2019.[3]

SOUTH KOREA

South Korea signed multiple MOUs with Saudi Arabia in the winter of 2022, including an agreement on cooperation between Korea's Hyundai Rotem and the Saudi Ministry of Investment for the NEOM rail system, Korea's state-of-the-art 3D modular construction for future cities in Qiddiya and the Red Sea, and cooperation between five Korean construction companies and the Saudi Public Investment Fund (PIF) on green hydrogen and new energy. Memoranda of understanding were also signed on cogeneration (KEPCO), gas and petrochemicals (Daewoo E&C), gas-insulated switchgear (Hyosung Heavy Industries), and a hydrogen ammonia cooperation agreement (KEPCO). Support was agreed for the joint development of hydrogen-powered trains (MOTIE 2022). The $6.5 billion project is to be built between 2025 and 2029 on a 396,694-square-meter site in Yanbu, Saudi Arabia, and is expected to produce 1.2 million tons of green hydrogen and ammonia annually.

In October 2022, Saudi Arabia's ACWA Power signed a Memorandum of Understanding (MoU) with Korea Electric Power Corp. (KEPCO), South Korea's largest electric utilities provider, to jointly develop industrial-scale green hydrogen and green ammonia projects. In South Korea, ACWA Power signed an agreement with POSCO Holdings in July 2022 to develop green hydrogen to decarbonize the latter's power generation and steel manufacturing processes.

[3] Further details can be found here https://www.eoiriyadh.gov.in/page/riyadh-declaration/

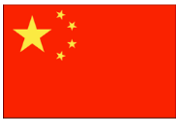
JAPAN

Japan and Saudi Arabia have issued the first offsets under their Joint Crediting Mechanism (JCM) program, for which Japan intends to use its share towards meeting its obligations under the Paris Agreement (Carbon Pulse 2020).

Bilateral trade between Saudi Arabia and selected countries in Asia can be found in following Table 3.

Table 3: Bilateral trade information for selected countries in Asia with key trade figures for 2021

Source: GASTAT

Bilateral Trade between  and the following country in Asia:	**OEC-World Link**	**Value export from Saudi Arabia in 2021 (bn USD)**	**Value import to Saudi Arabia in 2021 (bn USD)**
	**CN** https://oec.world/en/profile/bilateral-country/chn/partner/sau	**50.9**	**30.2**
	**IN** https://oec.world/en/profile/bilateral-country/ind/partner/sau	**26.7**	**8.1**
	**JP** https://oec.world/en/profile/bilateral-country/jpn/partner/sau	**27.4**	**6.1**
	**KR** https://oec.world/en/profile/bilateral-country/kor/partner/sau	**23.3**	**3.4**

Trade Relationships with Europe

BELGIUM

The BELGO-Luxembourg Economic Union (B.L.E.U.) signed an agreement with Saudi Arabia on 22-April 2001 concerning the reciprocal promotion and protection of investments. There is an established trade relationship between Saudi Arabia and Belgium (BFTA 2022).

FRANCE

France and Saudi Arabia signed an agreement on 27th September 2021, with the help of the two countries' national agencies, to promote investment. (GOV.FR 2021).

GERMANY

The Federal Republic of Germany has maintained diplomatic relations with the Kingdom of Saudi Arabia since 1954. The governments of both countries hold consultations regularly. Saudi Arabia is Germany's second most important trading partner in the Arab world after the United Arab Emirates (Federal Foreign Office 2020).

As one of the frontrunners in the hydrogen technology field, Germany can offer technology exchange across the entire value chain to accelerate the development and deployment of R&D and industry infrastructure in the Kingdom. This collaboration would foster an ecosystem of scientific advancements and innovation in the hydrogen economy, combining German expertise with local knowledge development. There is vital exchange between Saudi Arabia and Germany; some examples for recent cooperation in the field of hydrogen are:

- In March 2021: Saudi-German Hydrogen Cooperation launched implementation of bilateral hydrogen projects and exchange knowledge on technology and regulation to establish a hydrogen roadmap, three working groups have been established: technology, regulation and business.
- In February 2022, the 1st Saudi-German Energy Day in Riyadh took place.
- In February 2023, a Hydrogen off-taker meeting was held in the state of NRW.

The Kingdom has made considerable progress in hydrogen and CCUS technologies, with ongoing research at institutions such as KAUST, SABIC, and Aramco, contributing to advancements in hydrogen and energy carrier value chains.

However, several opportunities and R&D topics are ready for future collaboration between the institutes of the two countries. One of those opportunities is illustrated in the following paragraph:

Box 3: Energy transition and the upcoming hydrogen economy in Saudi Arabia

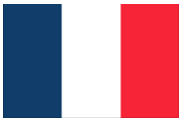
H2diplo Riyadh Office´s second study aims to provide background information and an analytical overview of Saudi Arabia's current key industries as well as products of relevance for its energy transition and its national hydrogen economy. In this context, the project team also explores what additional industrial sectors might be expanded or added to enhance the establishment of the energy transition's supply chains at a domestic level. By focusing on Saudi Arabia's current industrial production and its main industrial targets within the energy transition, the project sheds light on the kingdom's untapped industrial potential within the energy transition's supply chains and future perspectives for hydrogen production.

The project is funded by the Hydrogen Diplomacy Office in Riyadh, which was established by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) on behalf of the German Federal Foreign Office in 2022 to engage in a dialogue on Saudi Arabia's future role in the global energy transition.

Information about bilateral trade with Saudi Arabia and the selected countries from Europe can be found on the OEC website (see Table 4).

Table 4: Bilateral trade information for selected countries in Europe with key trade figures for 2021

Source GASTAT

Bilateral Trade between  and the following country in Europe:	**OEC-World Link**	**Value export from Saudi Arabia in 2021 (bn USD)**	**Value import to Saudi Arabia in 2021 (bn USD)**
	**BE** https://oec.world/en/profile/bilateral-country/bel/partner/sau	**4.9**	**1.9**
	**FR** https://oec.world/en/profile/bilateral-country/fra/partner/sau	**3.9**	**4.3**
	**DE** https://oec.world/en/profile/bilateral-country/deu/partner/sau	**0.5**	**7.5**
	**NL** https://oec.world/en/profile/bilateral-country/nld/partner/sau	**4.3**	**2.1**
	UK https://oec.world/en/profile/bilateral-country/gbr/partner/sau	**2.4**	**3.7**

Japan and Germany are expected to be significant net-hydrogen importing countries and have been particularly active seeking to develop bilateral partnerships and secure sufficient supply. Germany, for example, is currently examining - triggered above all by the war in Ukraine and the associated halt of imports of natural gas from Russia - which potential suppliers of green hydrogen will be able to provide the required energy quantities in the future.

The German hydrogen strategy foresees a growing hydrogen demand from 55–60 TWh today to 90–110 TWh by 2030. Around 20–25 TWh of demand is expected to be met by domestic production of hydrogen. Hence, **Germany will heavily rely on imports** (Guidehouse 2022b, p 3).

3 Net-zero target & hydrogen ambitions of Saudi Arabia's main trading partners

In this chapter the same two key off-taker regions in Europe and Asia are analyzed from a hydrogen development perspective (target state). The first step is to present the targets that Saudi Arabia's major trading partners have set for reducing emissions at home. In a second step, the focus is on the role of hydrogen in the Kingdom's main consumer markets in Europe and Asia in the context of the energy transition and net zero targets. The self-consumption of hydrogen and its derivatives in Saudi Arabia is presented in a third step.

An overview of the industrial applications of hydrogen is summarized in Table 5. Until the year 2030 these applications will play a key role as has been explained in chapter 2.4.2.

Table 5: Summary of hydrogen use in industrial applications and future potential

Source: (IEA 2019, 90f)

Sector	Current hydrogen role	2030 hydrogen demand	Long term demand	Low-carbon hydrogen supply	
				Opportunities	Challenges
Oil refining	Used primarily to remove impurities (e.g. sulphur) from crude oil and upgrade heavier crude. Used in smaller volumes for oil sands and biofuels.	7% increase under existing policies. Boosted by tighter pollutant regulations, but moderated by lower oil demand growth.	Highly dependent on future oil demand but likely to remain a large source of demand in 2050, even in a Paris-compatible pathway.	Retrofit natural gas or coal-based hydrogen with CCUS. Replace merchant hydrogen purchases with hydrogen from low-carbon electricity.	Hydrogen production and use are closely integrated within refining operations, making a tough business case for replacing existing capacity. Hydrogen costs strongly influence refining margins.
Chemical production	Central to ammonia and methanol production, and used in several other smaller-scale chemical processes.	31% increase under existing policies for ammonia and methanol due to economic and population growth.	Hydrogen demand for existing uses is set to grow despite materials efficiency (including recycling); new ammonia and methanol demand could arise for clean uses as hydrogen-based fuels.	Retrofit or new-build hydrogen with CCUS. Use low-carbon hydrogen for ammonia and methanol production (urea and methanol will still require a source of carbon).	Competitiveness of low-carbon hydrogen supplies depends on gas and electricity prices. CCUS retrofitting is not a universal option.

Sector	Current hydrogen role	2030 hydrogen demand	Long term demand	Low-carbon hydrogen supply	
				Opportunities	Challenges
Iron and steel production	7% of primary steel production takes place via the direct reduction of iron (DRI) route, which requires hydrogen. The blast furnace route produces by-product hydrogen as a mixture of gases, which are often used on site.	A doubling under existing policies as the DRI route is used more, relative to the currently dominant blast furnace route.	Steel demand keeps rising, even after accounting for increased materials efficiency. 100% hydrogen-based production could dramatically increase demand for low-carbon hydrogen in the long term.	Retrofit DRI facilities with CCUS. Around 30% of natural gas can be substituted for electrolytic hydrogen in the current DRI route. Fully convert steel plants to utilize hydrogen as the key reducing agent.	All options require higher production costs and/or changes to processes. Direct applications of CCUS are usually projected to have lower costs, although these are highly uncertain. Long term competition from direct electrification.
High-temperature heat (excluding chemicals and iron and steel)	Virtually no dedicated hydrogen production for generating heat. Some limited use of hydrogen-containing off-gases from the iron and steel and chemical sectors.	9% increase in high-temperature heat demand under existing policies. No additional hydrogen use without significant policy support.	Heat demand is likely to rise further, providing an opportunity for hydrogen if it can compete on cost in the prevailing policy environment.	Hydrogen from any source could replace natural gas, e.g. in industrial clusters or near hydrogen pipelines. Blends with natural gas are more straightforward but less environmentally beneficial.	Hydrogen is expected to compete poorly with biomass and direct CCUS in general, but may prove competitive with direct electrification. Full fuel switches, or CCUS, tend to entail significant investment.

3.1 Emission reduction targets

Emission reduction targets in selected countries in Asia and Europe

The Paris Climate Agreement established Nationally Determined Contributions (NDCs) for CO_2 emissions (or equivalents for other greenhouse gases). Many countries have announced their intention to be CO_2 neutral by 2050 at the latest: the EU, Japan, South Korea, South Africa, Canada and the USA. China (klimareporter 2020) and Saudi Arabia (argusmedia 2022) have the same goal to achieve net zero greenhouse gas emissions by 2060.

India aims to reach net zero by 2070 and has submitted its Long-Term Low Emission Development Strategy (LT-LEDS) to the UNFCCC in November 2022 to combat climate change (INSIGHTSONINDIA 2021). This strategy, presented at COP27, outlines plans to triple India's nuclear power capacity over the next decade, become an international center for green hydrogen production, increase the proportion of ethanol in gasoline, develop an integrated, efficient, and inclusive low-carbon transportation system, and foster low-carbon development of electricity systems in line with development. India has pledged to generate 50% of its electricity from non-fossil fuels by 2030 and reaffirmed its goal to preserve forest cover, which serves as a carbon sink (BBC 2022).

Implemented by

Further information on individual country's emission targets and tracking of progress towards these targets, see https://climateactiontracker.org/.

In Europe, targets were laid down in the 2021 EU Climate Law: climate neutrality in 2050 and a 55% emission reduction in 2030 compared to 1990 levels. Details for the net zero targets in Europe can be found at https://climateactiontracker.org/countries/eu/net-zero-targets/.

Germany set very ambitious goals with climate neutrality by 2045 already as can be seen in Figure 27. In the past 31 years the CAGR for CO_2-emission abatement was -1.6% in total. While most sectors succeeded to contribute to this CO_2-reduction, the transport sector was hardly able to reduce CO_2 emissions in this period. A significant reduction of CO_2-emissions in the transport sector can be achieved by using either battery electric vehicles (BEV) or fuel cell electric vehicles (FCEV) – the latter using directly hydrogen or a derivate like methanol in combination with a direct methanol fuel cell (DMFC). The hydrogen or derivate option will most likely be applied for heavy transport because of the high battery weight and long time needed to charge it.

Greenhouse gas emission trends in Germany by sector 1990-2022

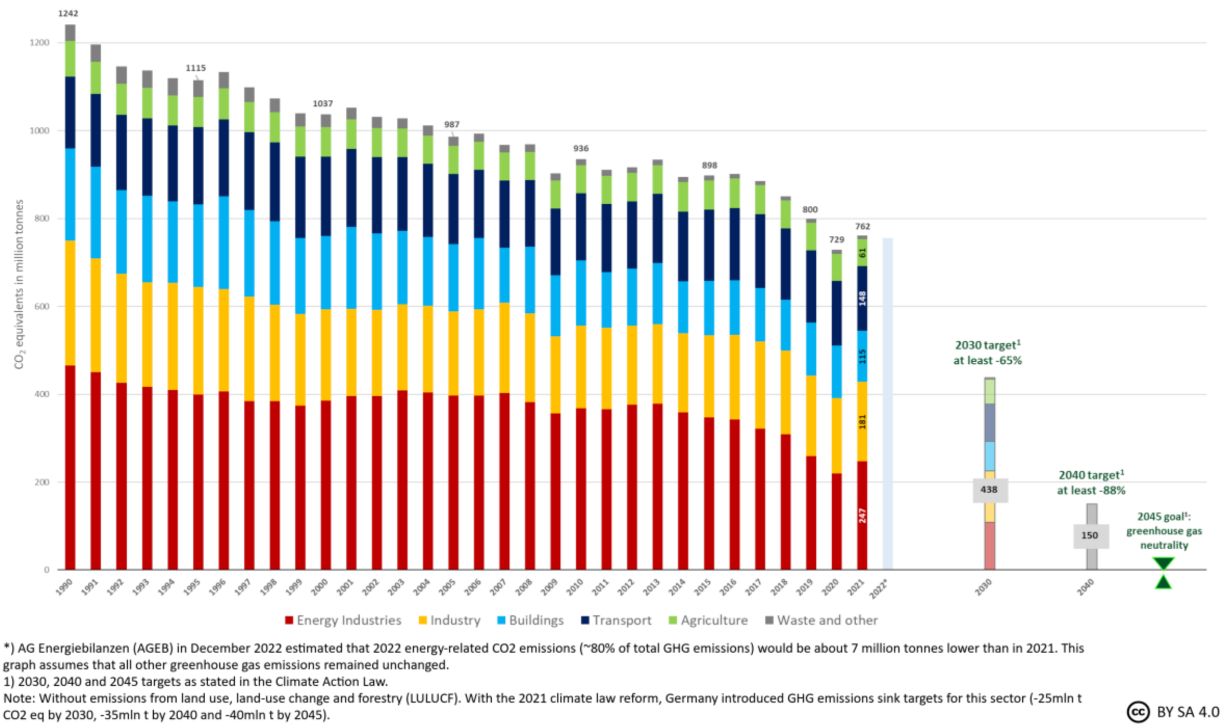


Figure 27: Greenhouse gas emission trends in Germany by sector 1990-2022

Source: (CLEW 2022), Data UBA 2022 (2021 data preliminary), AGEB.

Scenarios for the overall end energy system in Germany can be found in Figure 71 on page 114. The two main development trends, electrification and the use of hydrogen, are shown there in an exemplary manner.

The Circular Carbon Economy (CCE) Index developed by the Saudi Arabian advisory think tank KAPSARC is a very elaborated system which takes into account several other indices and indicators. The index values for different countries can be found at the following website: https://cceindex.kapsarc.org/cceindex/profiles/

The CCE Index can be used for benchmarking and as a guidance instrument for policy makers to fine-tune their carbon emissions reduction strategies.

3.2 Announced RE capacity extensions

RE capacity extensions planned in selected countries in Asia and Europe

China's climate pledge (its "nationally determined contribution", or NDC) aimed for 1,200 GW of wind and solar power capacity by 2030, and for 25% of energy consumption to be met by non-fossil fuels by 2030. For comparison: About 336 GW wind power capacity was installed in China end of 2022 of which 30 GW was installed in offshore wind parks and installed PV capacity amounted to about 393 GW (IRENA 2023b). Achieving these goals is expected to ensure China's carbon dioxide (CO_2) emissions peak before 2030, but to fall short of a pathway towards carbon neutrality.

China announced new offshore wind projects with broad application prospects. It can be used not only for local consumption at deep-sea oil and gas fields as a power supply for those offshore facilities, but also to develop marine pastures, seawater hydrogen production, marine tourism and marine mineral resources (Xinhua 2023).

India aims to install 500 gigawatts (GW) of renewable energy by 2030. In addition, it recently rolled out a green hydrogen plan with an initial allocation of $2.45 billion to lead research and development works to demonstrate the feasibility of green hydrogen (IEEFA 2023).

South Korea has ambitious offshore wind farm projects in the planning stage, which are dedicated for the production of hydrogen. Further details can be found in chapter 3.4.4.

Germany has set itself ambitious targets with the new Renewable Energy Sources Act (EEG 2023): By 2030, up to 600 terawatt hours (TWh) of electricity are to be generated annually from renewable energies, compared to around 240 TWh today. In 2030, photovoltaic (PV) systems totaling around 215 GW are expected to be installed (compared to about 67.4 GW net installed PV capacity end of 2022 in Germany – see https://energy-charts.info/).

For onshore wind turbines, the target is an installed capacity of around 115 GW in Germany by 2030 from about 58 GW installed end of 2022 (BMWK 2022, translated by authors). The expansion target for offshore wind energy increases to at least 30 GW by 2030. By 2035, at least 40 GW and by 2045 at least 70 GW of installed capacity are to be reached. For comparison: at the end of 2022, around 8.1 GW of offshore wind energy systems were installed.

In the United Kingdom, the ambition is for 40 GW offshore wind by 2030 according to the UK Hydrogen Strategy (BEIS 2022b, p 14).

On average cost for large-scale PV systems decreased by 15.5% each year in the last decade according to IRENA data. In absolute numbers, in 2021 total utility-scale PV system costs were -80.8% lower than 10 years before as can be seen from Figure 28.

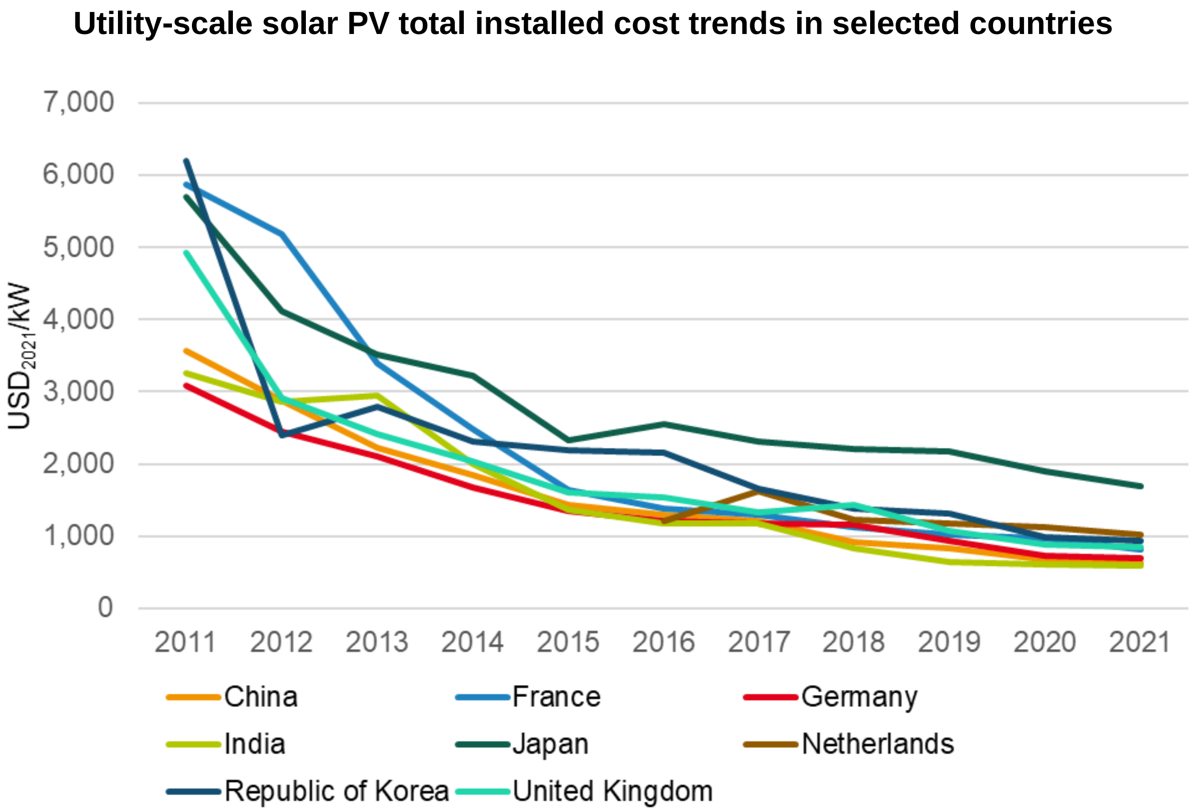


Figure 28: Cost trends for utility-scale PV systems in selected countries

Source: (IRENA 2022a, Figure 3.4 adapted by PSE Projects)

Note: Data were not available for all countries investigated in this report.

A detailed cost breakdown is provided for 2021 in Table 6. While India has the lowest total installed costs, Japan has the highest costs.

The rapid and continuous decline in the cost of renewable energy and its storage confirms the direction already taken by some countries and allows for the adoption of very ambitious net-zero strategies focused on green electricity and hydrogen production (MWN 2022 as an example).

Some insights about cost components might help to understand the difference between the selected countries. In Table 6, the colors indicate the lowest (marked dark green) and the highest cost (marked red) per component and row. For example, Japan has the highest installation costs, while Saudi Arabia has the highest costs for grid connection. So, the table can be used as a kind of cost benchmark and reasons for undesired high cost components should be analyzed. However, cheaper is not always better; for example, too little spending in the monitoring of the PV plant can have a negative impact on quality assurance and, in the worst case, underperformance of the PV system is not detected, resulting in longer-lasting yield losses.

Table 6: Detailed breakdown of utility-scale solar PV total installed costs by country, 2021 (USD_{2021}/kW)

	Cost component	Japan	Nether-lands	Republic of Korea	Saudi Arabia	United Kingdom	France	Belgium	Germany	China	India
Module and inverter hardware	Modules	288.7	331.5	320.4	376.0	369.2	280.2	316.4	339.4	216.3	286.0
	Inverters	114.3	47.7	74.8	32.0	36.0	48.5	43.6	46.0	26.3	29.9
BoS hardware	Racking and mounting	121.7	135.4	70.1	78.0	35.4	90.6	95.9	92.9	15.9	46.2
	Grid connection	87.4	70.1	89.7	112.0	41.8	104.0	39.3	12.5	72.7	27.0
	Cabling/ wiring	80.1	27.1	74.6	54.0	35.6	45.0	16.5	35.7	12.1	33.3
	Safety and security	13.7	37.5	10.3	8.0	12.7	7.6	21.1	5.4	12.0	15.2
	Monitoring and control	24.3	7.5	6.3	22.0	3.4	3.2	5.2	7.6	7.3	3.0
Installation	Mechanical installation	406.3	109.0	78.4	45.0	85.2	77.6	69.5	37.6	42.9	24.5
	Electrical installation	303.3	89.2	48.9	55.0	60.7	56.9	58.1	65.0	41.9	19.7
	Inspection	54.7	14.2	15.2	20.0	9.2	8.2	9.2	4.2	9.1	5.6
Soft costs	Margin	107.9	118.5	0.0	90.0	56.9	47.0	81.2	38.3	84.3	28.6
	Financing costs	23.9	7.0	96.6	7.0	41.9	3.4	5.2	2.6	37.7	38.4
	System design	13.2	9.8	16.5	15.0	8.8	8.7	7.6	3.0	13.5	5.9
	Permitting	32.2	8.0	25.7	11.0	38.2	12.9	5.4	1.8	8.0	12.7
	Incentive application	21.5	3.6	13.0	7.0	13.0	10.9	3.4	1.4	11.3	10.5
	Customer acquisition	0.0	5.9	0.0	0.0	0.0	3.5	4.0	0.0	16.8	3.1
	Totals	**1,693.2**	**1,022.0**	**940.5**	**932.0**	**848.0**	**808.2**	**781.6**	**693.4**	**628.1**	**589.6**

Source: (IRENA 2022a, Figure 3.5 adapted by PSE Projects)

Note: The colors indicate the lowest (marked dark green) and the highest cost (marked red) per cost component in each row.

3.3 Role of hydrogen today (applications)

The amounts of hydrogen and derivates consumed in industry and the applications are presented in this chapter for each region in more detail.

Main target sectors of current H_2 strategies per country

Hydrogen use sectors	EU	DE	NL	FR	ES	IT	UK	NO	CH	UA	RU	JP	KR	CN	AU	CA	MO
Industry	✓	✓	✓	✓	✓	(✓)	✓	✓	✗	✗	✓	(✓)	✗	✗	✓	(✓)	✓
Power	(✓)	(✓)	(✓)	✓	(✓)	✗	✓	✗	✗	✓	✓	✓	✓	✓	✓	(✓)	(✓)
Transport	✓	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	(✓)	✓	✓	✓	✓	✓	(✓)
Buildings	(✓)	(✓)	(✓)	(✓)	✗	✗	(✓)	✗	✗	(✓)	(✓)	✓	✓	✗	(✓)	(✓)	(✓)
Export	✗	✗	✗ 1)	✗	✓	✗	✗	✗ 2)	✗	✓	✓	✗	✗	✗	✓	✗	✓

✓ main sector (✓) less relevant ✗ not addressed

1) Hydrogen imports transit to other counties (e.g. Germany) considered.
2) For Norway, hydrogen is not targeted for direct export, but indirectly through the export of NG with local CCS.

Figure 29: Hydrogen use sectors in different countries

Source: (WEC & LBST 2020, p 13)

As shown in Figure 29, the main target sectors of current hydrogen strategies are generally industry and transport in Europe, while FR and UK also have a focus on power generation or stabilization of their power grid. In Asia, Japan and South Korea focus on the transport, power and buildings sector. China's focus is on transport and power. Countries planning to export H_2 or PtX are Spain, Ukraine, Russia, Australia and Morocco. Not shown here, but announced in their hydrogen strategies, countries from Latin America like Chile and Uruguay also consider exporting hydrogen and derivates.

With progress in the energy transition and a high share of volatile renewable energy generation capacity in the grid, a solution must be found to stabilize the grid. Consequently, by the author's assessment,

H_2-based electricity storage and power generation capacity could play an important role in backup power generation to balance out the intermittent renewable energies such as solar and wind. This is especially true for island states (like Japan) or where there is no energy trade with neighboring countries (South Korea).

To assess the potential of renewable power generation the following Table 7 shows the population, land area and resulting population density as well as the GDP. Also, conclusions about the energy demand can be drawn from these numbers.

Table 7: Population, population density and GDP in selected countries

Country	cca 2	Region	Population in Thousand (in 2021)	Land area (in square km)	Population density ↓	GDP (Mio. US$ in 2021)
South Korea	KR	Asia	51,744.88	97,600	530	1,810,956
Netherlands	NL	Europe	17,533.04	33,670	521	1,012,847
India	IN	Asia	1,407,563.84	2,973,190	473	3,176,295
Belgium	BE	Europe	11,592.95	30,280	383	594,104
Japan	JP	Asia	125,681.59	364,500	345	4,940,878
United Kingdom	UK	Europe	67,326.57	241,930	278	3,131,378
Germany	DE	Europe	83,196.08	349,390	238	4,259,935
China	CN	Asia	1,412,360.00	9,424,703	150	17,734,063
France	FR	Europe	67,749.63	547,557	124	2,957,880
Saudi Arabia	SA	MENA	35,950.40	2,149,690	17	833,541

Source: Worldbank Statistics:

Population: https://data.worldbank.org/indicator/SP.POP.TOTL, 2021

GDP: https://data.worldbank.org/indicator/NY.GDP.MKTP.CD, 2021

Land area: ehttps://data.worldbank.org/indicator/AG.LND.TOTL.K2, 2020

Note: The table is sorted in descending order by population density, expressed in number of people per square kilometer and calculated by dividing population by land area.

India and China have almost the same populations as Table 7 shows. However, mainland China has more than three times the land area of India. China's gross domestic product (GDP) is also more than five times that of India. It can be concluded that China has roughly a three times higher potential to install renewable energy systems compared to India because of the large available land. Also, China has a much higher economic power than India to perform an energy transition. However, when it comes to primary energy consumption, China is a “hungry dragon” as shown in Figure 17 on page 30 and Figure 18 (first left pie chart on page 31) and it will take enormous efforts and high investments to complete the coal phase-out in China and achieve climate neutrality as targeted until 2060.

Japan is shown in the middle of the table in terms of population density. This is somewhat deceptive because, due to the morphology of the Japanese islands, often only the coastline can be populated and the mountains are difficult to access. South Korea is the most densely populated country, and with the exception of building integrated photovoltaics (BAPV/BIPV) and offshore wind, the potential for renewable energy is limited.

3.4 Announced hydrogen and PtX production and consumption in selected countries

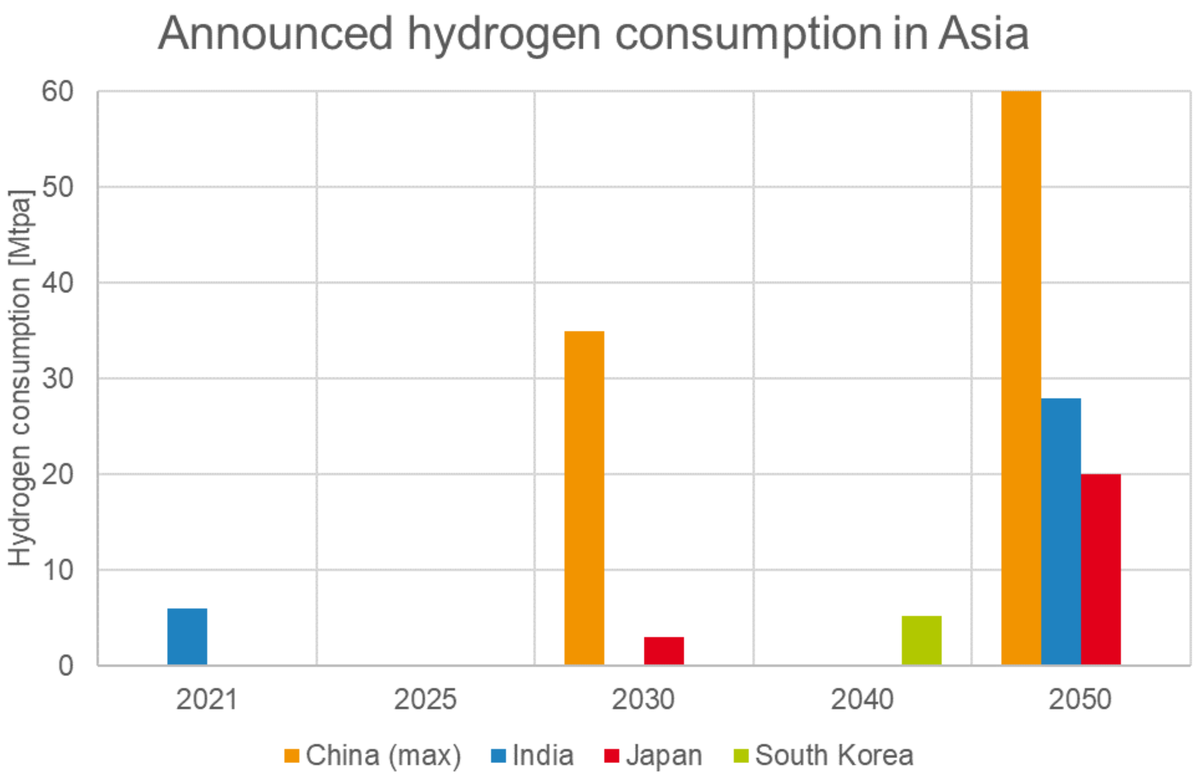


Figure 30: Announced hydrogen consumption in Asia

Sources: CN (CSIS 2021b); IN (FTI CONSULTING 2020); JP (GOV.JP 2021); KR (CSIS 2021b)

Note: For China a range from 12 to 35 million metric tons of H_2 is provided for 2030. The maximum value is shown in the graph. Not for all countries a value is provided in each time period.

Annual hydrogen production from renewable energy is expected to reach 100,000-200,000 tons in China to become an important part of new hydrogen energy consumption by 2025 and enable carbon dioxide emission reduction of 1-2 million tons/year (Mtpa) (Xinhua 2022).

The China Hydrogen Alliance has projected that renewable-based hydrogen production could reach 100 Mt by 2060, accounting for 20% of China's final energy consumption (CSIS 2022a).

Both Japan and South Korea will see a steep increase in their hydrogen demand in the foreseeable future. The combination of (nearly) insular character, the presence of very large industries or constrained geography will maintain both countries in their energy importer position.

India should also experience an increasing in demand for hydrogen. Though multiple support schemes for domestic hydrogen production have been announced, the steeply growing Indian economy might resort to further large imports, next to domestic production, to match its substantial demand.

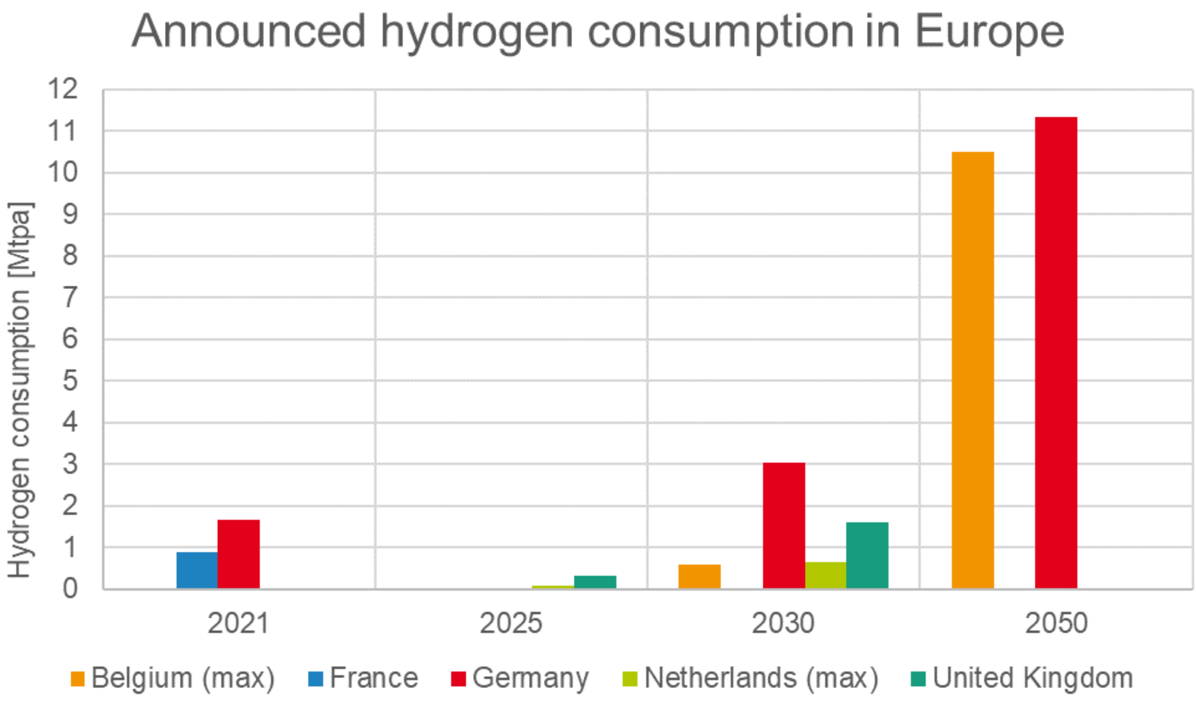


Figure 31: Announced hydrogen consumption in selected European countries

Sources: BE* (GOV.BE 2022, p 21); FR (GOV.FR 2020, p 4); DE* (BMWi 2020, p 9); NL** (GOV.NL 2020, p 7); UK** (GOV.UK 2022, 4ff)

Note: Not for all countries a value is indicated for each period.
*Calculated from TWh in metric tons of H_2 (1 TWh = 20'000 tons of H_2)
**Calculated from Electrolyser capacities (1 GW electrolyser is @8000 full load hours 160'000 metric tons of H_2)
Belgium: The total domestic demand for both, H_2-molecules and H_2-derivatives, will raise to 125 – 200 TWh/year in Belgium by 2050 (bunkering fuels included). In the graph, the maximum value is used.
Netherlands: Electrolyser capacity is provided with a range from 3 to 4 GW in 2030. The higher value is shown in Figure 31.

In 2021, primary energy production by renewables in Belgium was 48.4 TWh according to Statbel. Belgium was one of the first countries in the world to develop offshore wind production and has recently committed itself to almost triple its offshore wind capacity to reach 5.4-5.8 GW by 2030 and to look to increase the capacity further to 8 GW. H_2-molecules will be responsible for 30-60% of the demand in molecules by 2050 while the remaining 40-70% will go for other derivatives like e-ammonia, e-methane, e-methanol or e-kerosine. The federal government estimates the total domestic demand for both H_2-molecules and H_2-derivatives between 125 and 200 TWh/year in Belgium by 2050 (bunkering fuels included). This volume will mainly be driven by industry and international transport. Bunkering fuels are the fuels consumed in international maritime and air transport. Due to their role in international trade, their consumption is not allocated to a specific country according to international statistical standards. However, the load of these bunkering fuels in Belgium is not negligible since they currently represent an annual consumption of about 100 TWh according to Statbel. Belgium, with its ports and infrastructure integrated into the so-called European hydrogen backbone, a pipeline interconnection grid in Central Europe, could play a large role as a hydrogen gateway to Europe. It is estimated that this transit activity could double the volumes of imports forecasted for Belgian domestic consumption, totaling to an amount of 20 TWh in 2030 and 200-350 TWh in 2050 of imports of renewable molecules, for which about half is available for transit to Belgium's neighboring countries (FGOV.BE 2022).

In the hydrogen strategy of France, budget targets are mentioned, but neither electrolyser capacity growth nor hydrogen consumption targets. An update of the national strategy for the development of hydrogen is announced by the end of the first half of 2023 (GOUV.FR 2022, translated by authors).

Hydrogen Production Potential & Cost in 2050 [Mtpa]

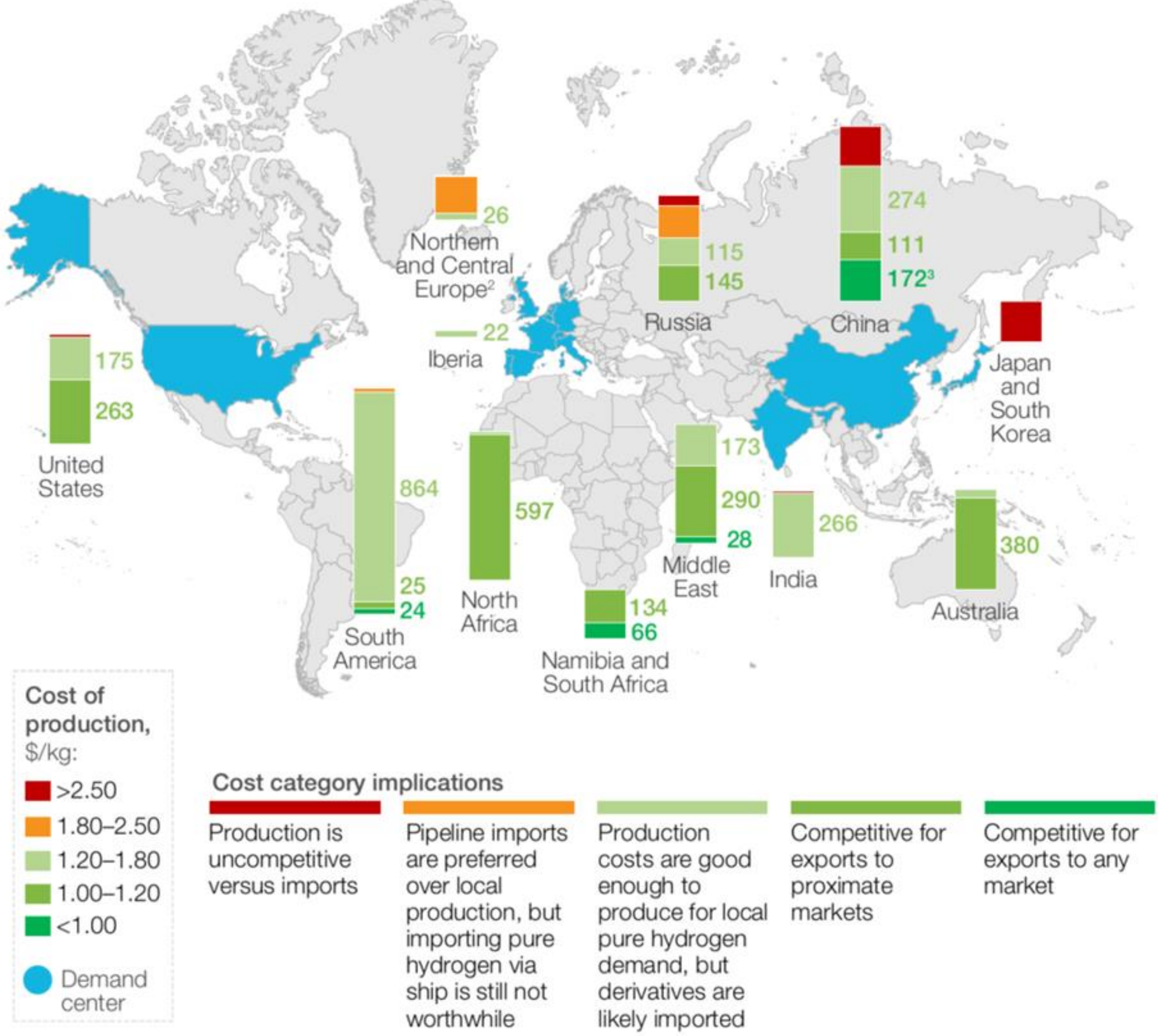


Figure 32: Hydrogen Production Potential & Cost in 2050 (million tons per annum)

Source: (H2C 2022, p 12)

Notes:

1. Potential for renewables and low-carbon hydrogen, constrained by a maximum of 0–3% land availability.
2. Only includes third-tier production potential, assuming that the higher-tier locations use renewable power.
3. Low-cost production in western China that requires long-distance transport to eastern China.

The European Union has great ambitions for hydrogen. It already announced in its hydrogen strategy the ambition to produce 1 million tons of H_2-molecules (6 GW electrolysis) by 2024 and to reach 40 GW electrolysis by 2030. Since then, the Union raised its ambitions to 10 million tons of domestic production of H_2-molecules by 2030 with its RepowerEU plan (FGOV.BE 2022, p 17).

Box 4: Calculation of produced hydrogen from electrolyser capacity

One calendar year has 8766 hours. If an electrolyser runs 95% of the time full load, it will produce hydrogen with its nominal capacity for 8328 hours annually. Economic feasibility is given if an electrolyser runs more than 4’000 FLHs per year (IEA 2019, p 47). With an electrolyser capacity of 1 Gigawatt and 8000 full load hours, about 0.16 to 0.18 Mio. tons of hydrogen can be produced per year. About 44 to 50 MWh of electrical energy is needed to produce 1 metric ton of hydrogen (World Bank Group 2022). The amount of electrical energy needed is depending on the electrolyser technology.

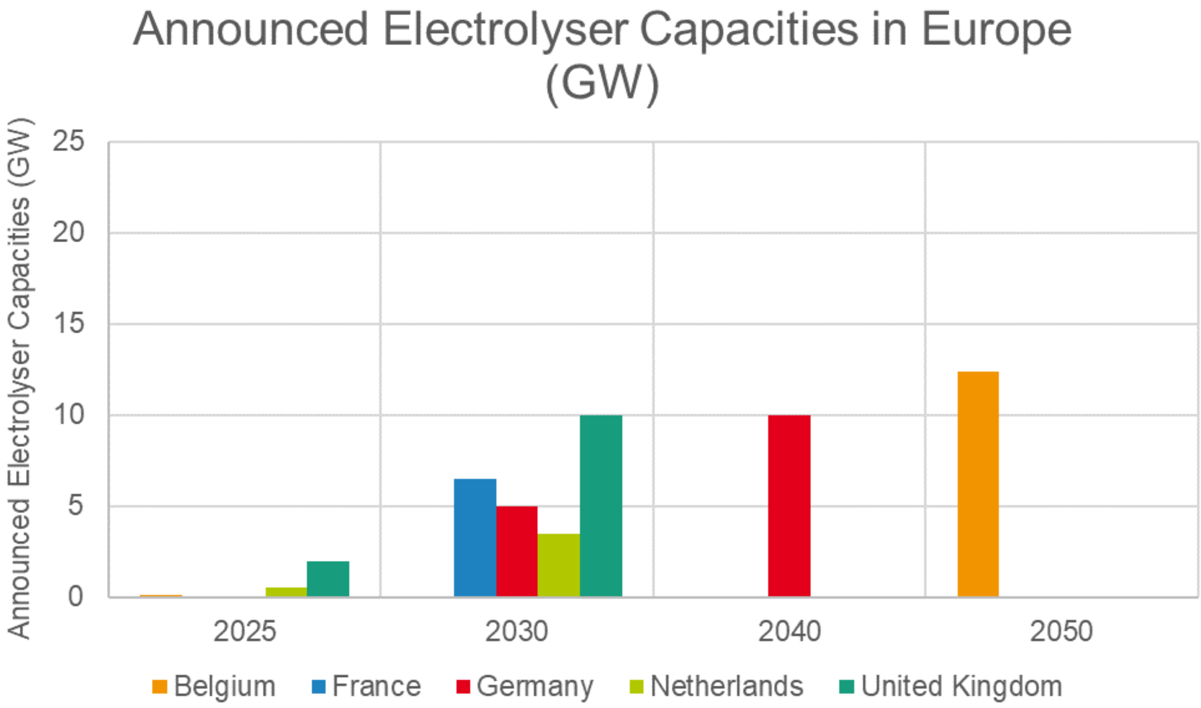


Figure 33: Announced electrolyser capacities in selected countries in Europe

Sources: BE* (GOV.BE 2022, p 21); FR (GOV.FR 2020, p 4); DE* (BMWi 2020, p 9); NL** (GOV.NL 2020, p 7); UK** (GOV.UK 2022, 4ff)

Note: Not for each years numbers are available from national roadmap documents.

Today’s hydrogen usage and ambition per category (transport, energy, building, energy efficiency measures etc.) and the role hydrogen will play in the industry (steel, cement, ceramic, glass etc.) in the concerned off-taker markets are to be investigated in this section in more detail for the selected countries.

3.4.1 China

China is the largest producer and consumer of hydrogen in the world with about 25 million tons (Mt), this is roughly a quarter of the global total (CSIS 2022a). Its hydrogen production increased by 6.8% annually since 2010. In 2020, about 62% of the hydrogen produced in China came from coal, 19% from natural gas, 1% from electrolysers, and the remaining share from by-products of industrial processes (Carbon Pulse 2021). China has nearly 1,000 coal gasifiers in operation, accounting for 5% of the country’s total coal consumption (Cleantech group 2019).

The Chinese government has established clear goals and objectives and has outlined several roadmaps and plans related to hydrogen and renewable energy development since 2016. China has always been heavily dependent on foreign energy sources and related key technologies. However, according to the national strategic plans, domestic production is to be increased while reducing import dependence on energy and related key products and technologies. China has a wealth of natural resources with immense potential to expand hydrogen production capacity. However, there is still potential for development in terms of infrastructure to exchange energy and energy carriers between provinces and there are limitations in storage technology, recharging infrastructure and fuel cell electric vehicle (FCEV) application. The country is catching up fast and invests for example in transport infrastructure such as railways. So, China is likely to become the APAC hub for hydrogen production. China is already a leader in renewable energy equipment manufacturing, especially in producing solar PV components. As such, China might gradually build on its geographic, technological assets to enhance domestic energy production, decreasing its reliance on imports. If this scenario does unfold, China totaling 25% of Saudi hydrocarbon exports, a shift in energy trade relations would emerge.

The Chinese government announced it will increase its production of green hydrogen, leveraging its advantage in renewables and focusing on R&D efforts to overcome limitations in domestic hydrogen equipment manufacturing (KAS 2022, p 31). As an outlook until 2030, it can be assumed that the production and application of green hydrogen in China will experience a phase of exponential growth. Currently, however, the country is only in the early stages of such a development. According to the Chinese government's roadmap, China has set itself the goal of reducing the price of green hydrogen to a level similar to that of natural gas by 2023 (KAS 2022, p 35). Already today, China is the largest producer of electrolyser with an electrolyser manufacturing capacity in 2022 of 7.6 GW/year – for comparison Europe has a capacity to manufacture 4.0 GW/y, North America 1.6 GW/y, India 0.5 GW/y and other unspecified regions 0.1 GW/y (IEA 2022a).

Currently two green hydrogen projects are under development in China:

1. The first one started in 2021 in the city of Kuqa, located in China's Sinkiang Uyghur Autonomous Region. With a total investment of $470.8 million, the project will produce an annual output of green hydrogen reaching 20,000 tons when put into operation. The project comprises five main sections: photovoltaic power generation (300 MW capacity with about 618 GWh expected annual power generation), power transmission and transformation, hydrogen from water electrolysis, hydrogen storage (210,000 m³) and hydrogen transmission pipelines with a capacity of 28,000 m³ per hour (including supporting power transmission and transformation facilities). In spring 2023, the project with an expected reduction of carbon dioxide emissions by approximately 485,000 tons a year (SINOPEC 2021) is reported to be 80% complete.

2. The second one just started in February 2023 as the world's largest project to produce green hydrogen, generated from renewable energy without carbon dioxide (CO_2) emissions in the city-prefecture of Ordos in north China's Inner Mongolia Autonomous Region with favorable solar and wind resources. Sinopec Star Petroleum, a subsidiary of the Sinopec company is responsible for the project. Both, hydrogen and green oxygen generated in the project are expected to be piped to the deep coal processing project, replacing existing methods. When operational, the facility is expected to generate 30,000 tons of green hydrogen and 240,000 tons of green oxygen annually, which could reduce CO_2 emissions by around 1.43 million tons per year (ATB Digital 2023).

With the second project in Ordos, China produces hydrogen (and oxygen) with an energy content of approximately 1 TWh per year. Concerning the total primary energy consumption of China, which was 40,437 TWh (equivalent to 145.5 EJ) in 2020 according to BP energy statistics, such projects can only contribute little to the total energy demand. However, one needs to consider that in a transformed energy system the overall energy efficiency will be two- or threefold better than in the established one. Electrification (for example the use of electric vehicles and heat pumps) and green hydrogen production can increase the efficiency of the total energy system significantly and so reduce the primary energy consumption. Both projects demonstrate that China is serious about transforming its energy system and is ambitious to produce renewable hydrogen to reduce the consumption of coal.

Over 90% of hydrogen is currently used as industrial feedstock to produce ammonia, methanol and for petroleum refining (Carbon Pulse 2021). Ammonia synthesis is the largest source of hydrogen consumption in China, with a domestic production of 57,6 Mt in 2019 and a hydrogen consumption of over 10 Mt. In contrast to the rest of the world where steam methane reforming (SMR) is the main route for ammonia production, the most common feedstock in China is coal, via a partial oxidation process. About 76.7% of China's ammonia production comes from coal, 20.8% from natural gas, 2.1% from coke oven gas and 0.5% from other sources (Ifri 2020, p 15).

Methanol synthesis is the second largest source of hydrogen consumption. In 2019, China produced 62.2 million tons of methanol which implied an annual hydrogen consumption of about 8 million tons. Around 76% of the domestic methanol production is derived from coal, 17% from coke oven gas and 7% from natural gas (Ifri 2020, p 16).

Petroleum refining is also a major source of hydrogen consumption, amounting to approximately 4.5 Mt in 2019 (ibid.).

Although China is showing a growing interest in the development of hydrogen in the transport sector, it represents only a small share of today's hydrogen demand (IEA 2021b).

The vast potential for renewable-based hydrogen production and the significant energy consumption profile may mean that China would become neither an exporter nor an importer of hydrogen – the country would become self-sufficient. The transportation sector, particularly trucks and buses, may remain China's focus for hydrogen application, although hydrogen use in industrial sectors seems to be emerging (CSIS 2022a).

3.4.2 India

India, as well as Pakistan and Bangladesh, is suffering from volatile and raised prices for fossil energy carriers like oil, LNG and coal. High energy prices caused by the Russian war against Ukraine have impacted different sectors, from power generation to industries. Power outages and a negative impact on the economies of these countries are the consequences. Falling prices for renewables in South Asian countries will support their clean energy plans and could be a game changer to counter high global energy prices. Renewable energy expansion could shield South Asian countries from massive price volatility in the international energy markets and reduce energy security and current account risks (IEEFA 2023). However, huge investments are needed to establish such renewable and hydrogen-based energy infrastructure.

In 2020, India's hydrogen demand stood at 6 million tons per year (Mtpa). The government announces to produce 5 Mt of green hydrogen in 2030. It is estimated that by 2030, the hydrogen costs will be down by 50%. Industrial applications for hydrogen are the production of fertilizer, steel (DRI) and petrochemicals. Also transport and stabilizing the electrical grid are foreseen as hydrogen applications to replace fossil fuels (MNRE 2022). Two applications are highlighted in the 'National Hydrogen Mission' of India:

- India's annual ammonia consumption for fertilizer production is about 15 Mt, roughly 15% of this demand (over 2 Mtpa) is currently met from imports. Mandating even 1% green ammonia share is likely to save about 0.4 million standard cubic feet per day of natural gas import.

- Use of hydrogen in the steel industry could substitute imported coking coal. During 2018-19, the total demand for coking coal for the steel industry was 58.4 Mt. Out of this, 51.8 Mt was met through imports. (MNRE 2022).

In the transport sector, the following advantage of hydrogen is seen in India: While battery electric vehicles (BEVs) depend on imported raw materials such as lithium and cobalt for lithium-ion batteries, the supply chain for hydrogen fuel cells can be established entirely domestically, making India independent in the clean transport segment.

The demand for hydrogen is expected to see a five-fold jump to 28 Mt by 2050 where 80% of the demand is expected to be green in nature. India has declared its ambition to become an exporter of hydrogen to Japan, South Korea, and Europe (MNRE 2022).

India is today slightly more populated than China, but has only about one-third the land surface of China. India enjoys favorable solar conditions for PV systems in Rajasthan, but grid infrastructure is not very advanced and extension of the grid must be taken into account with its high investment costs. **Therefore, it can be expected that India will also rely on imports of energy carriers for a longer period.**

In March 2023 it was reported that the Japanese IHI Corporation has signed a memorandum of understanding with ACME, a leading renewable energy company in India, to study and investigate the feasibility of producing and utilizing green ammonia derived from renewable energy. IHI will also consider participation in green ammonia production projects, which ACME has been developing, in Oman, India, the USA and Egypt, as well as the use of ammonia for power generation for decarbonization in Asian islands and others (RTS 2023, p 23). **This can be seen as an indicator that green ammonia is the "fuel of the future" also in the Indian energy market.**

Even though its plans are getting more ambitious in the upcoming H2-economy, multiple constraining parameters will maintain India in a position of an energy net-import nation for the foreseeable future.

3.4.3 Japan

The existing hydrogen strategy was released in December 2017. Renewable energy power generation, including traditional hydro power generation, accounts for only 15.0% (estimated for FY2016) of Japan's total power generation (METI 2017, p 8). The Japanese hydrogen strategy comprises:

- Expected demand (according to green growth strategy): 3 Mt by 2030, 20 Mt by 2050.
- **Focus on hydrogen imports** (fossil and renewable) due to the lack of domestic resources.
- Long term strategy: In 2050, carbon neutral accomplishment; grid parity of fuel cells in 2025.
- Hydrogen application expected in power generation, transport, heating and industry.
- Strong focus on hydrogen technology development and export of advanced technology (e.g. fuel cells).

Regarding supply chains the following considerations are made: currently, Japan uses compressed or liquefied hydrogen for supply. To develop international supply chains, carriers like methylcyclohexane (MCH), ammonia, and methane could be used alongside liquefied hydrogen. Each carrier has pros and cons, and technological, safety, and environmental challenges must be addressed while developing the necessary infrastructure (METI 2017, 20f).

The following routes are discussed in the paper (METI 2017, 21ff):

a) Developing liquefied hydrogen supply chains

b) Developing organic hydride supply chains

c) Developing technologies for utilizing ammonia as an energy carrier

d) Considering methanation using CO_2-free hydrogen

e) Domestic hydrogen transportation through pipelines

In pilot projects the feasibility of these routes is investigated. To highlight the route a) Developing liquefied hydrogen supply chains, Japan and Australia are jointly developing a liquefied hydrogen supply chain, aiming for commercialization and utilizing brown coal for CO_2-free hydrogen production. They have also pioneered liquefied hydrogen carrier ships, with tentative safety standards adopted by the International Maritime Organization in 2016 (METI 2017, p 21).

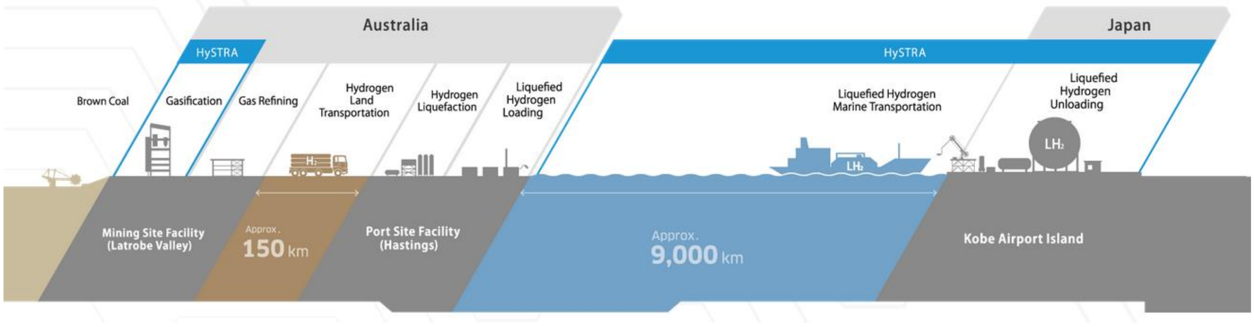


Figure 34: Scheme for the Japan-Australia liquefied hydrogen supply chain development and demonstration project HySTRA

Source: https://www.hystra.or.jp/en/project/

Similar pilot projects have been launched to explore other ways of transporting and using hydrogen. Consequently, the development of infrastructure for mobility and harmonization of regulations, codes, and standards are on the action plan of the Japanese government (METI 2019). Research on fuel cells is part of the program. In September 2020, Saudi Aramco exported the world's first carbon-neutral ammonia shipment to Japan, marking a significant milestone in the hydrogen economy for both Saudi Arabia and Japan. The 40-ton pilot shipment demonstrates the growing potential of this emerging industry (KAPSARC 2020, p 3). Several research and demonstration projects are initiated in Japan to optimize direct combustion of ammonia as a fuel. Japan has a strong specialization in ammonia cracking, which is the process to release pure hydrogen from ammonia, with 61% of the international patent families (IPFs) published in that field and eight of the top ten applicants in that field in the period 2011–2020 (IEA 2023b, 56f).

In sum, based on its own strategy, its high population density, its insular character and energy-intensive industries, Japan is set to remain largely an energy importer. As such, major suppliers will continue considering it as a key off-taker market.

3.4.4 South Korea

South Korea adopted the Hydrogen Economy Roadmap in 2019 and has set the goal to be CO_2 neutral by 2050 at the latest (see climateactiontracker.org/countries/south-korea/policies-action/; the site provides also valuable information for progress to climate neutrality for other countries). A Hydrogen Law, which went into effect in 2021, stipulates several important industrial strategy elements, such as supporting hydrogen-focused companies through subsidies for research and development, loans, and tax exemptions.

South Korea's annual hydrogen consumption is 130,000 tons in 2021 and it aims to expand it to 5.26 million tons/year in 2040 (CSIS 2021b).

By 2020, South Korea led the world in fuel cell electric vehicle (FCEV) installation, with over 10,000 FCEVs on the road, doubling the national stock from 2019. Accordingly, the hydrogen refueling stations (HRSs) as a key infrastructure is strongly increasing: from 24 HRSs in 2019 to 310 HRSs in 2022 and 1,200 HRSs scheduled by 2040. At present, about half the cost of installing HRSs is subsidized by the government (CSIS 2021b). The government of South Korea plans to foster an increase in the number of hydrogen-powered cars from 4,000 in 2019 to 6.2 million by 2040 and make the country the No. 1 producer of hydrogen powered cars and fuel cells globally by 2030 (RVO.NL 2019).

South Korea aims to deploy 15 GW of utility-scale fuel cells to increase grid stability (CSIS 2021b).

The following Figure 35 provides evidence that already about 375 MW of fuel cells were installed in South Korea in 2019 while almost 99% at utilities to generate power.

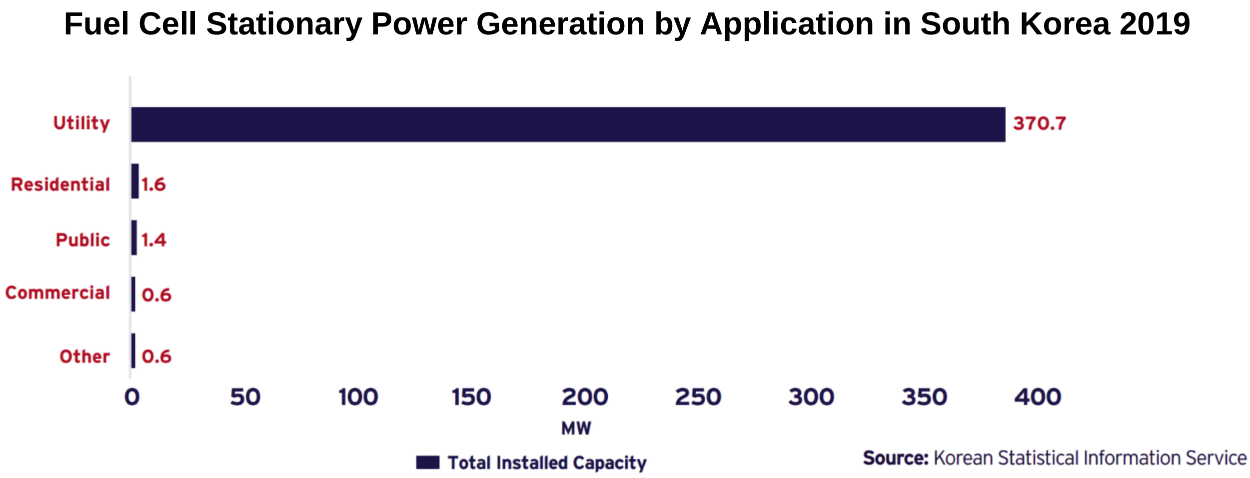


Figure 35: Fuel Cell Stationary Power Generation by Application in South Korea 2019

Source: (DIT 2021, p 9)

South Korea's efforts also include R&D on liquefied hydrogen storage technology and the reduction of transportation costs. Additionally, the roadmap notes the government's long-term aim of building a specialized hydrogen pipeline network across the country while the development of hydrogen-receiving infrastructure is set to begin in 2022. While about one-third of the country's hydrogen consumption in 2040 is estimated to be based on imported liquefied natural gas (LNG), South Korea's state-run utility, KOGAS, plans to invest $37 billion overseas by 2040 to establish renewable power generation facilities that produce hydrogen (CSIS 2021b).

South Korea is reportedly exploring various projects with potential hydrogen resource suppliers, such as Australia and Saudi Arabia. For example, Hyundai OilBank Co. plans to take liquefied petroleum gas (LPG) cargoes from Saudi Aramco, convert the LPG into hydrogen, and ship back the carbon dioxide that was emitted in the process back to Saudi Arabia. Additionally, South Korea and Norway announced in 2019 their cooperation on shipbuilding for liquefied hydrogen transportation (CSIS 2021b).

South Korea also has ambitious offshore wind farm projects in the pipeline. The generated power will run electrolysers and produce green hydrogen for the local industry – for example to produce green steel. The city of Gwangyang will be transferred into a "hydrogen city" as part of its budget for the period 2023-2026 (REVOLUTION ENERGETIQUE 2023).

South Korea is pumping large sums of money into the development of a national hydrogen economy. It has just signed a 48.5 trillion won ($38 billion) contract to build the world's largest offshore wind farm. It will be located off the Sinan Islands, in the extreme south of the country. With an announced capacity of 8.2 GW, it will supply 100% renewable electricity to around 3 million inhabitants. A thousand wind turbines should be erected, based on the average power of an offshore turbine (7.8 MW in Europe in

2019). Its commissioning, scheduled for 2030, will drastically reduce the share of fossil fuels in the South Korean electricity network. The country currently uses 40% coal, 26% natural gas and 25% nuclear power to produce its electricity. Renewable energy, which accounts for only 5.6% of the local energy mix today, is expected to increase to 20% within ten years, predominantly by wind turbines (REVOLUTION ENERGETIQUE 2021).

This decision is the culmination of a policy initiated by Seoul in mid-2022 **to reduce the cost of clean energy by 50%**. The country is counting on the project to supply 430,000 cars a year with low-cost "clean" fuel. The industrial city of Gwangyang was chosen to host the project because it has the basic infrastructure to produce, store and transport hydrogen. Gwangyang is located on the border of Jeolla Province and has a port, managed by Yeosu Gwangyang Port Corporation, and a steel mill, Posco Gwangyang, which is the fourth largest producer in the world. Both entities are stakeholders in the project.

According to the forecasts of the project initiators, hydrogen is to take a priority position among energy sources for domestic use as well as in the transport sector. The pilot operation will initially involve public transport and cleaning vehicles, which will now be powered by hydrogen. A public opinion survey will be conducted in parallel. Converting an internal combustion engine vehicle to hydrogen is more complex than converting to a battery electric vehicle, but it is still possible. The internal combustion engine can be retained and adapted to burn hydrogen instead of gasoline, or it can be removed to make room for an electric motor powered by a fuel cell.

In the second stage, the operation will reach residential areas, sports centers and other infrastructures, via hydrogen fuel cell installations. Finally, Yeosu Gwangyang Port Corporation's is developing tractors and drones powered by hydrogen fuel cells.

The project involves the **construction of 19 km of hydrogen pipelines** between the hydrogen electrolysers, the **Posco steel plant**, the refuelling stations, the fuel cells and the port of Gwangyang. On the strength of this experience, Seoul is being approached by countries such as Saudi Arabia, with which contracts have already been signed in November 2022 (REVOLUTION ENERGETIQUE 2023).

South Korea specializes in battery technologies and also has revealed technological advantages (RTA) in solar PV and nuclear energy, hydrogen and fuel cells, plus low-carbon energy (LCE) end-use technologies in the ICT, consumer goods, maritime transportation and EV sectors. Hydrogen applications are expected to play a significant role in medium- to long-term energy storage in Japan and South Korea due to the need to manage the integration of electricity from volatile sources such as solar and wind into the grid and the absence of electricity trade with neighbouring countries.

Sharing nearly the same constraining parameters as Japan when it comes to limited domestic energy production, South Korea will further revert to major providers to quench its energy thirst.

3.4.5 Europe

In general, European countries aim to decrease their dependency on energy imports from Russia as a consequence of the Ukraine war. The Green Deal of the European Commission and ambitious national climate action plans underline that European countries are very serious about reducing CO_2 emissions in order to mitigate the effects of climate change. In the past, hydrogen was mainly used in oil refineries and ammonia production as depicted in Figure 36.

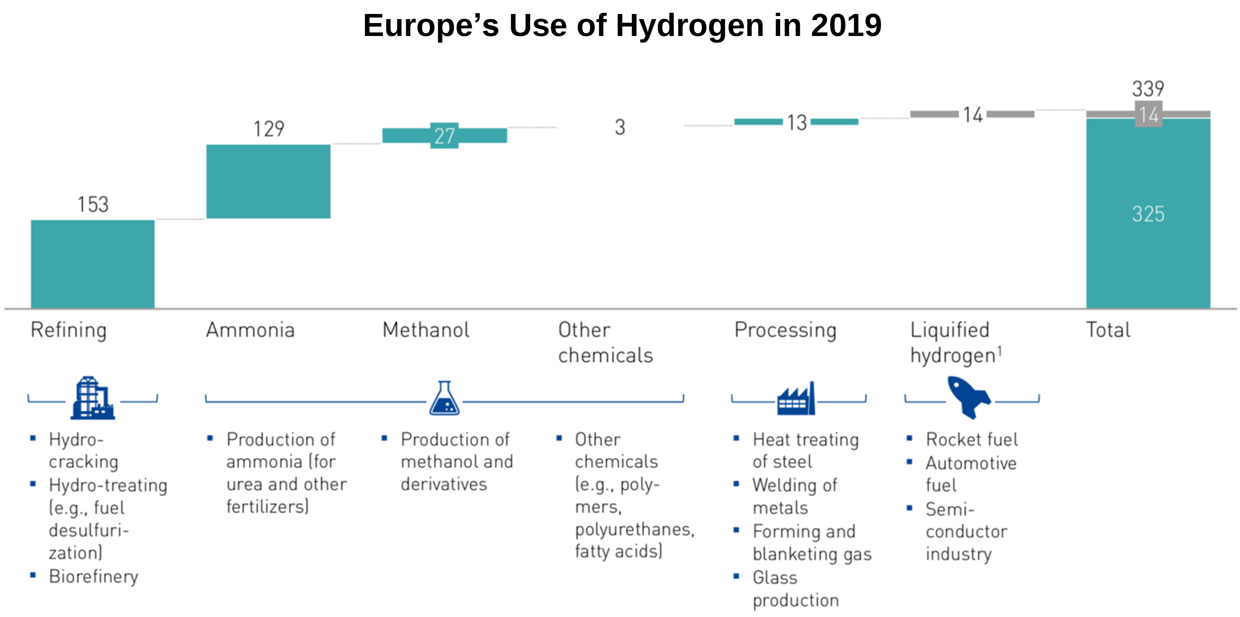


Figure 36: Total hydrogen use in the EU in the year 2019, in TWh

Source: (fch.europa.eu 2019, p 40)

Following the “Ambitious” scenario, hydrogen could provide up to 24% of the total energy demand, which is up to 2,250 TWh of energy in the EU28 by 2050 as shown in Figure 37.

Hydrogen Energy Demand until 2050 in EU28

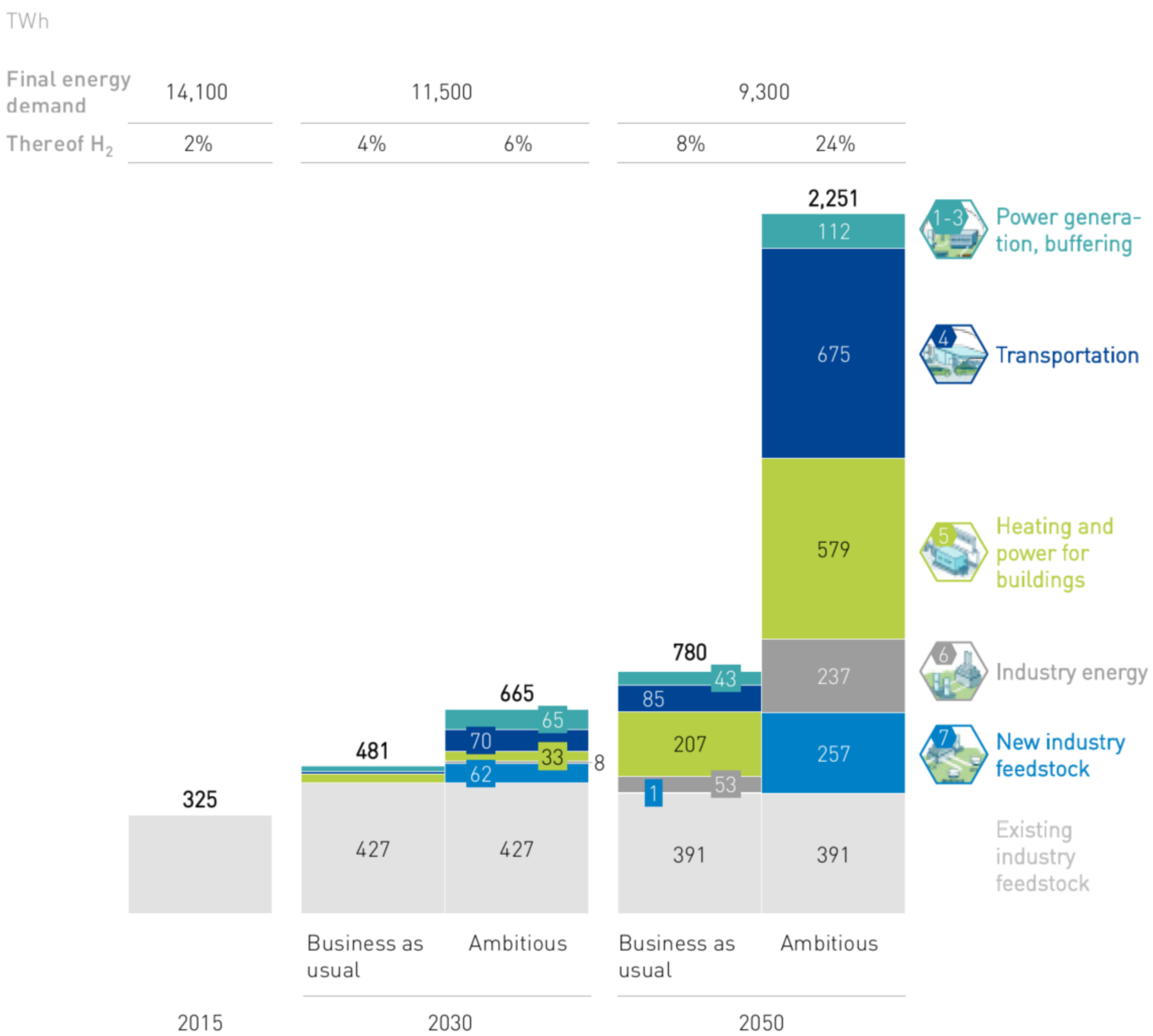


Figure 37: Hydrogen Energy Demand projection until 2050 in EU28 by Sector with BAU and Ambitious scenario

Source: (fch.europa.eu 2019, p 8)

Europe is projected to have 200 MW of electrolysis projects for oil refining by 2026, which are expected to generate approximately 14 kilotons of green hydrogen annually. Moreover, if favorable policies are adopted, an additional 1,100 MW of projects, which have not yet reached the final investment decision (FID) stage, may also come online in the same period (IEA 2021d, p 109).

The EU to offer 'fixed premium' to green hydrogen producers in an attempt to compete with US H_2 tax credits

As a reaction to the US hydrogen tax credits, the European Commission has unveiled plans to offer green hydrogen producers in Europe a "fixed premium" — the first time the bloc has committed to subsidize domestic production in this way. As part of the Green Deal Industrial Plan, the EU intends to carry out the first of a series of auctions this autumn for subsidies for renewable hydrogen production, with the winners offered a premium per kg of green H_2 for a period of ten years. Around $872 million will be available for the first auction, which will be funded under the auspices of the EU's $40.5 billion Innovation Fund (Hydrogeninsight 2023a).

The European Energy Exchange (EEX) has developed a platform for auctioning hydrogen and its derivatives aimed at governmental and commercial actors. End of June 2023, it signed its first Letter of Intent with Hintco, a Leipzig, Germany based subsidiary of H2Global Foundation, allowing them to auction renewable hydrogen and its derivatives, including ammonia, methanol, and aviation fuel, in a competitive and transparent manner. The key role of hydrogen in modernizing and decarbonizing industries and the importance of the trading platform for integrating hydrogen into the market has been highlighted. The expressed common goal is to develop a competitive European price signal for hydrogen and its derivatives, with a global impact. The H2Global concept implemented by Hintco aims to create and maintain transparency in the renewable hydrogen market by bundling supply and demand in standardized products. The first Hintco auctions via the EEX hydrogen platform could take place by the end of 2024.

3.4.6 Belgium

The Belgian government launched its Federal Hydrogen Strategy in 2021 to support the European Commission's goals and to prepare Belgium for the technological and economic challenges and opportunities arising from the greater adoption of H_2. The strategy is built around four pillars: Belgium as Europe's import hub for green H_2 molecules, Belgian leadership in H_2 technologies, the creation of a robust H_2 market, and greater cooperation (BCG 2022, p 4). In 2020 the annual consumption of hydrogen and its derivates was about 15 TWh which corresponds to 450,450 tons[4] of hydrogen (BCG 2022, p 9).

Industrial applications

Direct-reduced iron and electric arc furnaces (DRI-EAFs): In Belgium, ArcelorMittal Ghent has already announced it aims to convert one of its two blast furnaces to a DRI-EAF by 2030.

In chemicals, petrochemicals and refining value chains: low-carbon methanol, ammonia, kerosene, and synthetic methane, with pilot projects for producing green methanol having been established in Belgium.

Finally, low-carbon H_2 is expected to be the main means of decarbonizing industrial processes that require temperatures above 500°C. Industrial heating could account for 10-20 TWh of H_2 demand in Belgium by 2050, unless there are major breakthroughs in the electrification of high-temperature processes (BCG 2022, p 7).

Low-carbon fuels for shipping, aviation, and heavy-duty transport

According to BCG's forecasts, demand for low-carbon H_2 for marine bunkers and fuel for international aviation will reach at least 40 TWh p.a. nationally by 2050, potentially up to 75 TWh p.a. by 2050. Long-haul shipping is likely to be an especially important consumer of green ammonia and/or methanol in the future, representing the largest share of this demand. (ibid.)

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[4] Calculated with the calorific value of 1 kg H_2 = 33.3 kWh

Reducing CO_2 emissions in power generation and for grid stabilization

Whether in the form of low-carbon H_2 molecules or H_2 derivatives such as green ammonia, gas turbine OEMs and power generators have expressed the ambition to use low-carbon H_2 with existing gas turbines (with low-carbon H_2 typically representing a minor share of the feedstock) or new turbines over varying time horizons. (ibid.)

For obvious reasons shared with notably Germany or the Netherlands, Belgium will be an importer of hydrogen (and derivatives). Major future suppliers, such as Saudi Arabia, could through Belgium become one key provider for strategic European industries.

3.4.7 France

On 8th September 2020, the French government presented its national hydrogen strategy. The current market in France for hydrogen is about 1 million tons per year. An electrolyser capacity of 6.5 GW is announced to be installed in 2030 which can produce about 1 million tons of hydrogen with 95% of maximum full load hours. The French government sets $7.8 billion (€7bn) by 2030 in public support for the development of carbon-free hydrogen. The following three priorities are announced:

i. the decarbonization of industry to contribute to achieving carbon neutrality by 2050,

ii. the development of hydrogen-powered heavy mobility,

iii. support for excellent research and the development of training offers.

Research: Ademe launched two calls for projects in October 2020:

- to support innovations on technological bricks and demonstrators on fuel cells, high-pressure tanks and other complex systems dedicated to the use of hydrogen;
- to support, in the territories, supply and demand projects for renewable or carbon-free hydrogen by deploying infrastructures for the distribution of carbon-free hydrogen and the associated uses (GOUV.FR 2021).

The focus topics identified by the French strategy to support research, innovation and skills development to promote the uses of hydrogen are numerous. The following examples illustrate the diversity (GOUV.FR 2021):

- **hydrogen in energy networks:** hydrogen can be used to facilitate the deployment of renewable energies by improving the stability of energy networks;
- **new uses in the industry:** the use of carbon-free hydrogen can be integrated into certain industrial processes in order to reduce CO_2 emissions. Hydrogen could for example be used in the steel industry for the reduction of iron ore;
- **tomorrow's heavy mobility:** this is particularly the case for carbon-free planes and ships. The use of hydrogen by these sectors could be the subject of demonstrators;
- **tomorrow's H_2 infrastructures:** hydrogen has some potential to make the gas sector carbon-neutral in the medium term. (liquid H_2, reuse in the gas network).

France's ambition is to have at least four gigafactories and all the technologies needed to use hydrogen (GOUV.FR 2023). Based on these announcements and the fact that France generates electricity predominantly from nuclear energy, the country could play a double role in being both an importer and exporter of hydrogen.

3.4.8 Germany

Around 55 TWh of hydrogen – most of it produced from fossil energy sources – is used for industrial applications in Germany each year (BMWi 2020, p 6). This corresponds to about 1,652,000 metric tons of hydrogen, if the conversion is made using the calorific value (see footnote 4).

Germany aims to be CO_2-neutral already in 2045 (see Figure 27 at p. 47).

The greatest demand for hydrogen is linked to material production processes in industry and is evenly distributed between basic chemicals (production of ammonia, methanol, etc.) and the petrochemicals sector (production of conventional fuels). The bulk of the hydrogen being used in these processes is 'grey' hydrogen. About 7% of demand (3.85 TWh) is being met via electrolysis (chloralkali) processes. Since some of the hydrogen used in the petrochemicals industry, in particular, does not have to be produced from scratch, but is available as a by-product of other processes (e.g. catalytic reforming), the current level of hydrogen consumption of around 55 TWh cannot entirely be substituted with 'green' hydrogen (BMWi 2020, p 9).

It is estimated that more than 80 TWh (2.4 million tons) of hydrogen would be needed to make German steel production GHG-neutral by 2050. Around 22 TWh (0.66 million tons) of green hydrogen would be needed for German refinery and ammonia production to switch to hydrogen. Germany's industrial sector already has demand for hydrogen and this demand is expected to grow heavily in the future (BMWi 2020, p 6). **10 GW electrolyser capacity is envisioned to be installed by 2030 to produce green hydrogen, but this will not be sufficient to meet the demand and a large part of the hydrogen needed in Germany will have to be imported according to a presentation of BMWK in May 2023.**

The Federal Government of Germany will revisit and develop the regulatory framework and the technical requirements for the gas infrastructure. For example, it will examine whether natural gas pipelines, which are no longer needed to transport natural gas (for example L gas) can be converted into hydrogen infrastructure and investigate whether the compatibility of existing or upgraded gas infrastructure with hydrogen can be ensured.

Further applications are indicated in heavy vehicle transport and fork lifters as well as for energy transformation. In the long run, hydrogen and its downstream products can help in various ways to decarbonize parts of the heat market (BMWi 2020, p 10).

European collaboration is to be strengthened, but also international trade is seen to be fostered. If Germany is to reach its climate targets for 2030 and its GHG neutrality target by 2045, importing renewable energy from beyond the European internal market will become a medium- and long-term necessity. In this context, sustainable development with a focus on global CO_2 emission reduction targets and fair and equitable energy security is a fundamental principle of the German government (BMWi 2020, p 11).

The introduction of CO_2 pricing for fossil fuels used in transport and the heating sector is an important element to improve the framework for the efficient use of electricity from renewables and to achieve the CO_2 emission goals of the 2030 Climate Action Programme (BMWi 2020, p 16).

The German hydrogen strategy defines 38 measures spending 9 bn EUR until 2030 that must be oriented towards economic efficiency in addition to sustainability goals: High-priority in this case will be fields in which the use of hydrogen is close to being economically viable in the short or medium term, in which no major path dependency is being created, or in which there are no alternative options for decarbonization (BMWi 2020, p 17).

3.4.9 The Netherlands

The Dutch National Climate Agreement includes an ambition to scale up electrolysis to approximately 500 MW of installed capacity by 2025 and 3-4 GW of installed capacity by 2030.

The connection to the future hydrogen infrastructure and the spatial integration of electrolysis projects deserves particular focus.

Given the significant projected demand for zero-carbon gases by 2050 and the forecast that Dutch green gas production will not be able to fully meet this demand, the scaling up of the production of both green gas and hydrogen is essential. Alongside green gas, zero-carbon hydrogen will be indispensable in meeting the expected demand for zero-carbon gases (GOV.NL 2020, p 2).

Hydrogen is considered an important sustainable alternative to fossil diesel fuel to power inland vessels (GOV.NL 2021).

Europe's largest green hydrogen plant will be built on Maasvlakte 2. Shell has taken the final investment decision for this. The futuristic plant will be named Holland Hydrogen I and is expected to be operational in 2025. The 200 MW electrolyser will be constructed on the Tweede Maasvlakte in the port of Rotterdam and will produce up to 60 tons of renewable hydrogen per day. The renewable power for the electrolyser will come from the offshore wind farm Hollandse Kust (noord), which is partly owned by Shell. The renewable hydrogen produced will be supplied via the HyTransPort pipeline to Shell Energy and Chemicals Park Rotterdam, where it will replace some of the grey hydrogen used in the refinery. This will partially decarbonize the facility’s production of energy products like petrol and diesel and jet fuel. As hydrogen powered heavy-duty trucks are coming to market and refueling networks (HRS) grow, renewable hydrogen supply can also be targeted at them to contribute to the decarbonization of commercial road transport (Port of Rotterdam 2022).

However, at the same time, hydrogen imports will also take up a key role in the Netherlands as a global market begins to emerge (GOV.NL 2020, p 1).

3.4.10 United Kingdom

The 2020s roadmap set out in the UK Hydrogen Strategy showed how the British government anticipate that the use of hydrogen will increasingly decarbonize heavy industry and provide greener, flexible energy across power, transport, and potentially heat, through the 2020s and beyond (BEIS 2022a, p 8).

Low carbon hydrogen is seen as essential to achieving net zero and meeting the UK's ambitious Sixth Carbon Budget (CB6) target of reducing emissions by 78% from 1990 levels by 2035. Analysis by BEIS for CB6 suggests 250-460TWh of hydrogen could be needed in 2050 (BEIS 2021, p 9) making up 20-35% of the UK’s final energy consumption (see Figure 38). According to the UK Hydrogen Strategy, 5 GW of low-carbon hydrogen production capacity is to be created by 2030 (BEIS 2021, p 30).

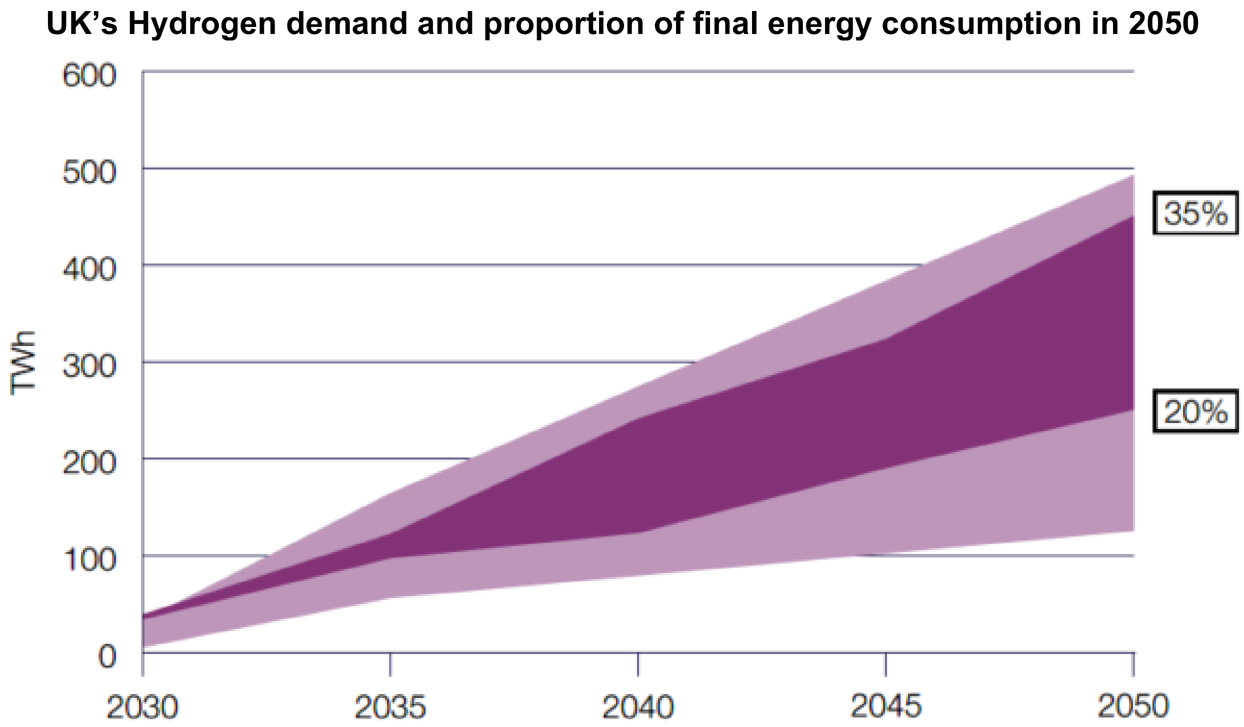


Figure 38: UK's Hydrogen demand and proportion of final energy consumption in 2050

Source: (BEIS 2021, p 9). Central range – illustrative net zero consistent scenarios in CB6 Impact Assessment. Full range – based on the whole range from the UK Hydrogen Strategy Analytical Annex. Final energy consumption from ECUK (2019).

Note: The percentage shown on the right of the graph refers to the share of hydrogen in total energy consumption in 2050 for the United Kingdom.

3.5 Expected import demand for hydrogen and PtX

The amount and which product do the off-takers require: pure hydrogen or a derivate (PtX)? This is outlined in the following section.

Expected hydrogen and PtX import demand in selected countries in Asia and Europe

The question of how much hydrogen and PtX will be produced domestically and what share will be imported cannot be answered precisely. However, a general assessment can be made:

Taking into account transportation costs, ammonia seems to be the best option for very long distances such as those represented by deliveries from Saudi Arabia to Asia. Methanol is on place two and liquified hydrogen a quite expensive option. Some infrastructure (vessels, port terminals, etc.) already exist in Saudi Arabia as well as in the selected countries.

Regarding the quantities of imported hydrogen or PtX: Japan and South Korea will certainly import a substantial part of their total primary energy demand and have signaled this. China and India have announced plans to be self-sufficient or even exporters. However, given the high energy demand of the world's two most populous countries, it will take decades to achieve this. Until then, both countries will definitely import significant amounts of energy sources to meet their needs.

For Europe in the overall strategy, about 50% of the hydrogen consumption will be based on imports in 2030. Belgium in its role as a hydrogen gateway to Europe announced that it will import significant quantities of renewable hydrogen and derivatives (20 TWh in 2030) It is estimated that this transit activity could double the volumes of imports forecasted for Belgian domestic consumption, totaling to an amount of 20 TWh in 2030 and 200-350 TWh in 2050 of imports of renewable molecules (GOV.BE 2022, p 6).

3.6 Trade routes for the importing countries to get access to hydrogen or its derivates

The transport possibilities to these off-taker markets, the hydrogen storage methods and infrastructure requirements are investigated in this section.

Japanese IHI CORPORATION and Emirates National Oil Company (ENOC), a national oil and gas company of Dubai, have signed a memorandum of understanding to study and investigate the feasibility of producing and selling green ammonia derived from renewable energy in Dubai and surrounding emirates. They will utilize the abundant PV resources. The two companies will consider ammonia sales business for export to the Japanese and other Asian markets, as well as for local power generation and marine fuel supply (Source: PV Activities in Japan and Global PV Highlights; RTS Corp. Vol. 28, No. 12).

In Figure 39 the costs to produce hydrogen (in USD per kg) for domestic production by three different paths (via renewables electrolysis, natural gas SMR plus CCUS and coal plus CCUS) and imports are compared for some regions. It can be concluded:

- Europe: Equal costs for Domestic production using intermittent renewable energy sources (IRES) and import – Targeted 50% import and 50% domestic production.

- Japan: Import of hydrogen or derivates has a clear cost advantage.

Shipping hydrogen between countries could emerge as a key element of a future secure, resilient, competitive and sustainable energy system. Investment in infrastructure, ships, standards and supply chain companies will have the most impact if located in regions with the greatest potential for hydrogen imports and exports. It is unlikely that they can be implemented on a large scale without multilateral cooperation among interested governments.

The cost of hydrogen production varies between regions, with Europe and Japan having relatively high costs and also strong policy support for hydrogen (Figure 39). Hydrogen importers stand to benefit from cheaper low-carbon energy, especially if their domestic renewable energy, nuclear or CCUS resources are challenging or expensive to develop. Hydrogen imports can help maintain energy security in a low-carbon future. Exporters stand to generate new sources of economic value based on clean energy resources. The Middle East could produce over 200 years of current hydrogen demand at $1.3/kg$H_2$ from known gas reserves that could be combined with CCUS. **Excellent solar and wind energy conditions will enable Saudi Arabia and its neighbors to produce green hydrogen at competitive prices by 2030.**

Routes for hydrogen trading with long term costs compared to domestic production

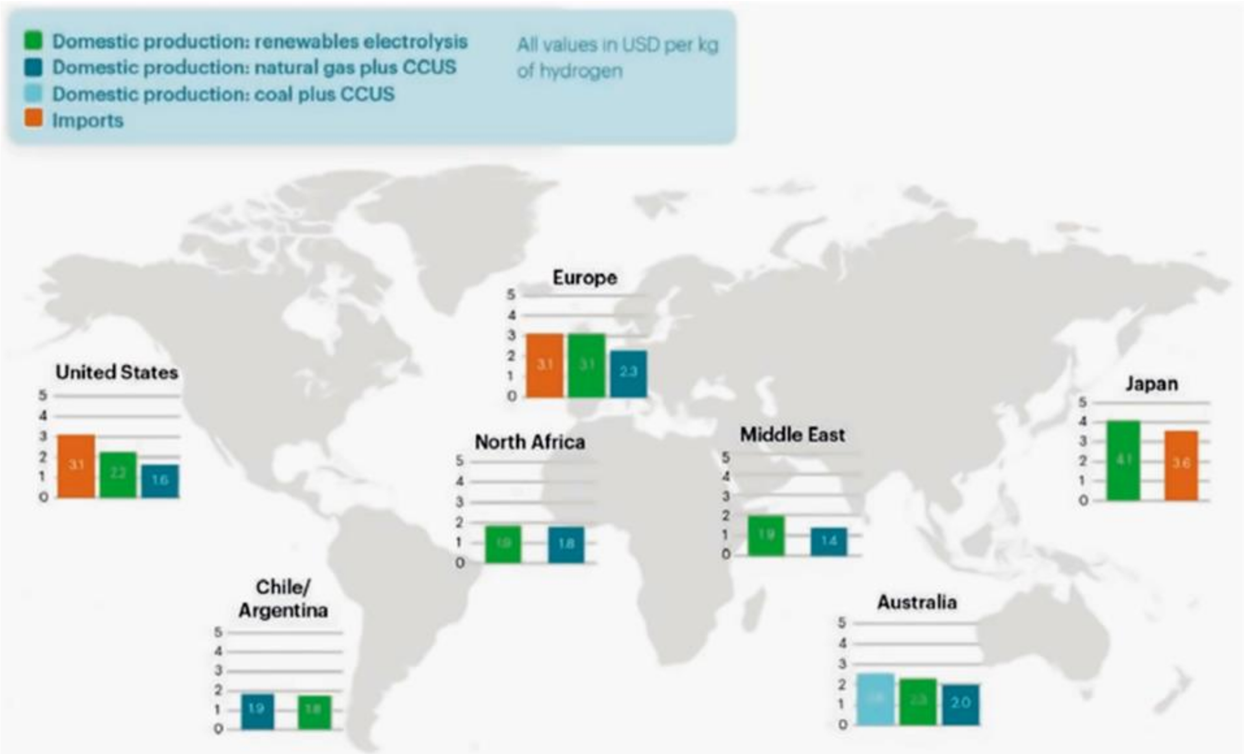


Figure 39: Routes for Hydrogen Trading with long term costs compared to domestic production

Source: (IEA 2019, p 189)

Notes: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and the name of any territory, city or area. Production cost reflects long term potential (i.e. low CAPEX for wind and solar, see Chapter 2). Electrolysis considers dedicated wind and solar production.

3.6.1 Pros & Cons of different transport options

Costs of different options for the long-distance transport of hydrogen depend on the transport distance

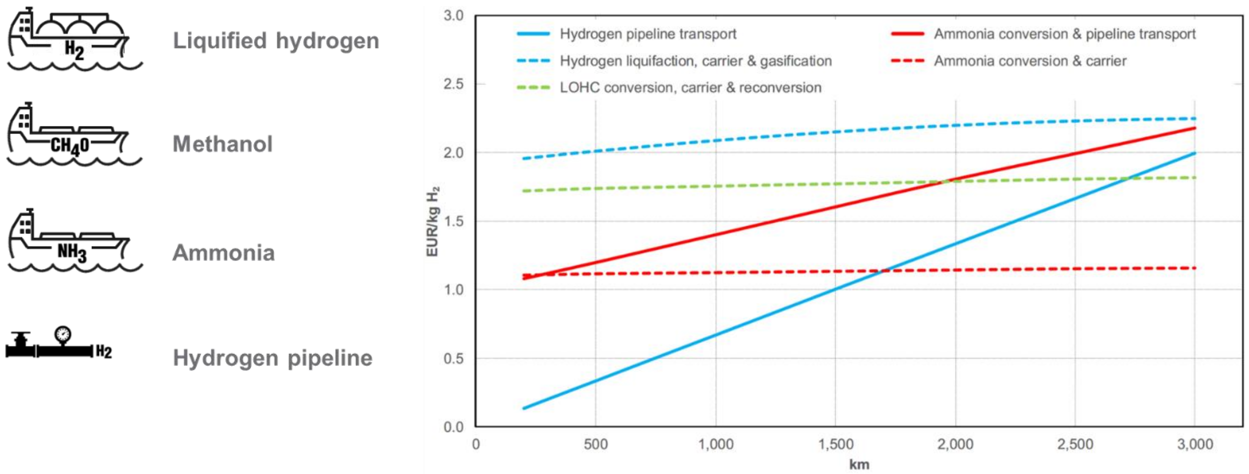


Figure 40: Hydrogen & PtX Transport - Options and Costs

Source: (Öko-Institut 2020, p 98) based on (IEA 2019), (Niermann et al. 2019) and (H2C 2020)

Economic and energy related arguments for:

- **Pipelines** (H_2 can also be mixed with natural gas in pipelines and re-extracted by the receiving end user). As Figure 40 indicates, pipelines are the least cost option for a distance up to about 2,000 km. It also depends on what the off-taker is using the H_2 or PtX for.

- **Maritime shipping** (liquified hydrogen, Liquid Organic Hydrogen Carrier = LOHC, Ammonia, Methanol). The dashed red line (Ammonia conversion and carrier) is the second cheapest option to transport PtX over a large distance. Hydrogen liquefaction is an energy-intensive process. The most recent hydrogen liquefaction plants have average electricity consumption of approximately 10 kWh/kg, equivalent to around 30% of the energy content (lower heating value) of hydrogen. Despite the relatively high energy needs, large hydrogen liquefaction terminals for export will likely be located in areas with access to low cost and low-emission electricity. Assuming electricity costs of $25 /MWh and the US Department of Energy (DOE) target of a future energy consumption of 6 kWh/kg hydrogen, electricity expenditures for liquefaction would be $0.15 /kg. However, electricity costs would only be a fraction of the hydrogen liquefaction costs, as the capital cost for liquefaction remains a major cost component that influences overall economic feasibility. The US DOE has set target for capital costs of large-scale hydrogen liquefaction plants (300 tons per day) at $142 million (excluding storage). This compares with current cost estimates of $560 million. (IEA 2022b, p 133).

3.6.2 Existing infrastructure and future needs

Ports

Where no transport by pipeline is feasible, a suitable port infrastructure can enable the shipping of hydrogen or PtX to export markets.

Pipelines

For Belgium, Netherlands, France and Germany the 'hydrogen backbone' consisting of a pipeline network to transport and exchange hydrogen plays an important role in the future. Also salt caverns, aquifers and depleted oil or gas fields will be used as hydrogen storage. Figure 42 shows the European coverage from Spain to the Czech Republic and from Sweden to Italy. The Hydrogen Backbone will supply industrial clusters via hydrogen pipelines based on existing natural gas pipelines as well as newly constructed H_2 pipelines.

Natural gas import pipelines with their potential H_2 import capacities

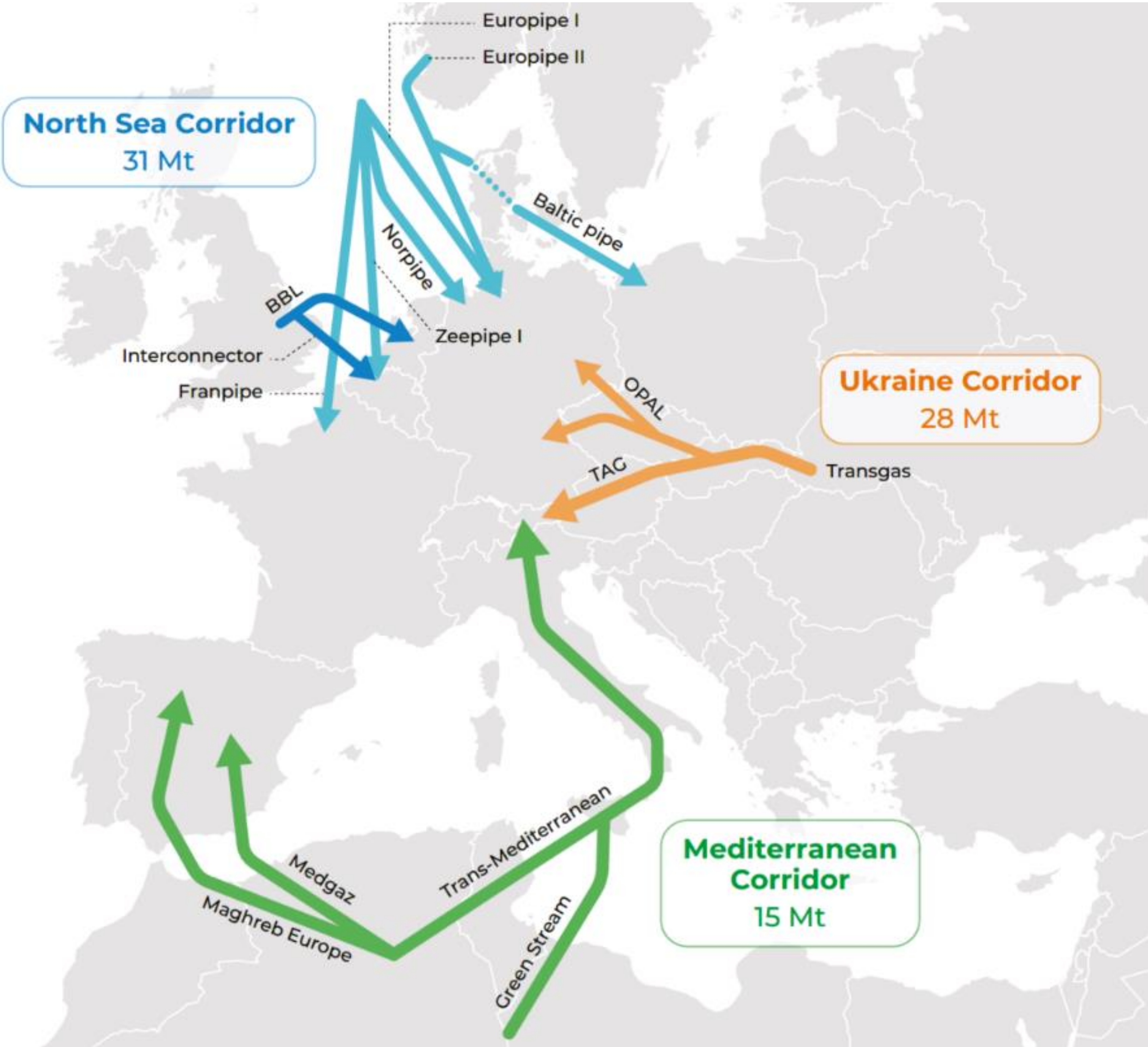


Figure 41: Natural gas import pipelines in Europe with their potential hydrogen import capacities

Source: (Guidehouse 2022a, p 10)

Note: Calculated by the relative energy density to natural gas (80%), given the pipeline volume capacity (Annex 1). e.g., 1 bcm natural gas ~9.8 TWh →1 bcm hydrogen = 7.8 TWh ~ 0.23 Mt of hydrogen

As shown in Figure 41, the existing pipeline network for natural gas, which is potentially suitable for importing hydrogen, does not have a direct connection point for Saudi Arabia.

Power grid

The existing power grid infrastructure also has some influence on decision making regarding hydrogen infrastructure. To give an example: If strong high-voltage connections already exist, it might be cheaper to transport the electricity and then produce hydrogen at the destination instead of building a hydrogen pipeline.

Conversion and storage infrastructure

Existing infrastructure that can be repurposed to a hydrogen-based energy carrier technology can save costs. For example, a greenfield conversion plant might cost much more than using an existing brownfield plant for Ammonia synthesis. Also, available storage capacities like salt caverns, aquifers or depleted gas fields can be used to store hydrogen.

Box 5: Converting parts of LNG terminals is feasible if considered in the design

Both ammonia and liquid hydrogen pose technical challenges to the terminal infrastructure. Ammonia has a more favorable boiling temperature than LNG and therefore lower thermal insulation requirements, but it is corrosive and toxic. Liquid hydrogen on the other hand has an even lower boiling point than LNG, can cause material embrittlement and has high safety requirements due to explosion risks.

LNG terminals consist of several components such as a storage tank, compressors, and pumps. The storage tank is the most expensive part. To avoid high new investments, the conversion to ammonia or liquid hydrogen should already be considered when designing the terminals, for example by using compatible materials like special stainless steel. Given this, it is estimated that approximately 70% of the LNG terminal investment can be further used for an ammonia terminal. For liquid hydrogen, next to material compatibility, additional thermal insulation of the tank is required or a higher boil-off has to be accepted. Economic impacts are more difficult to estimate due to a lack of industrial-scale infrastructure experiences. However, based on the share of the cost of the LNG tank, it can be projected, that approximately 50% of the LNG terminal investment can be further used, if material compatibility has been considered in the tank's construction and a higher boil-off is accepted. (Fraunhofer ISI 2022)

There is already some hydrogen infrastructure with H_2 pipelines, hydrogen storages and industrial clusters using hydrogen. The existing structure is mainly in Northern Europe and Germany, but an extension is planned until 2040 as can be seen in Figure 42. The existing pipelines for natural gas can either be blended with hydrogen or, if suitable, they can be converted to transport pure hydrogen.

China is the largest hydrogen producer and consumer in the world and has embraced the concept of hydrogen industrial clusters. At least 23 out of 31 provincial level regions in China have already issued development plans for hydrogen energy and fuel cell vehicles. China’s eager embrace of hydrogen industrial clusters is largely incentivized by the country’s ability to significantly bring down unit manufacturing costs through industrial clusters (WEForum 2021a).

Mature Hydrogen Backbone can be created by 2040

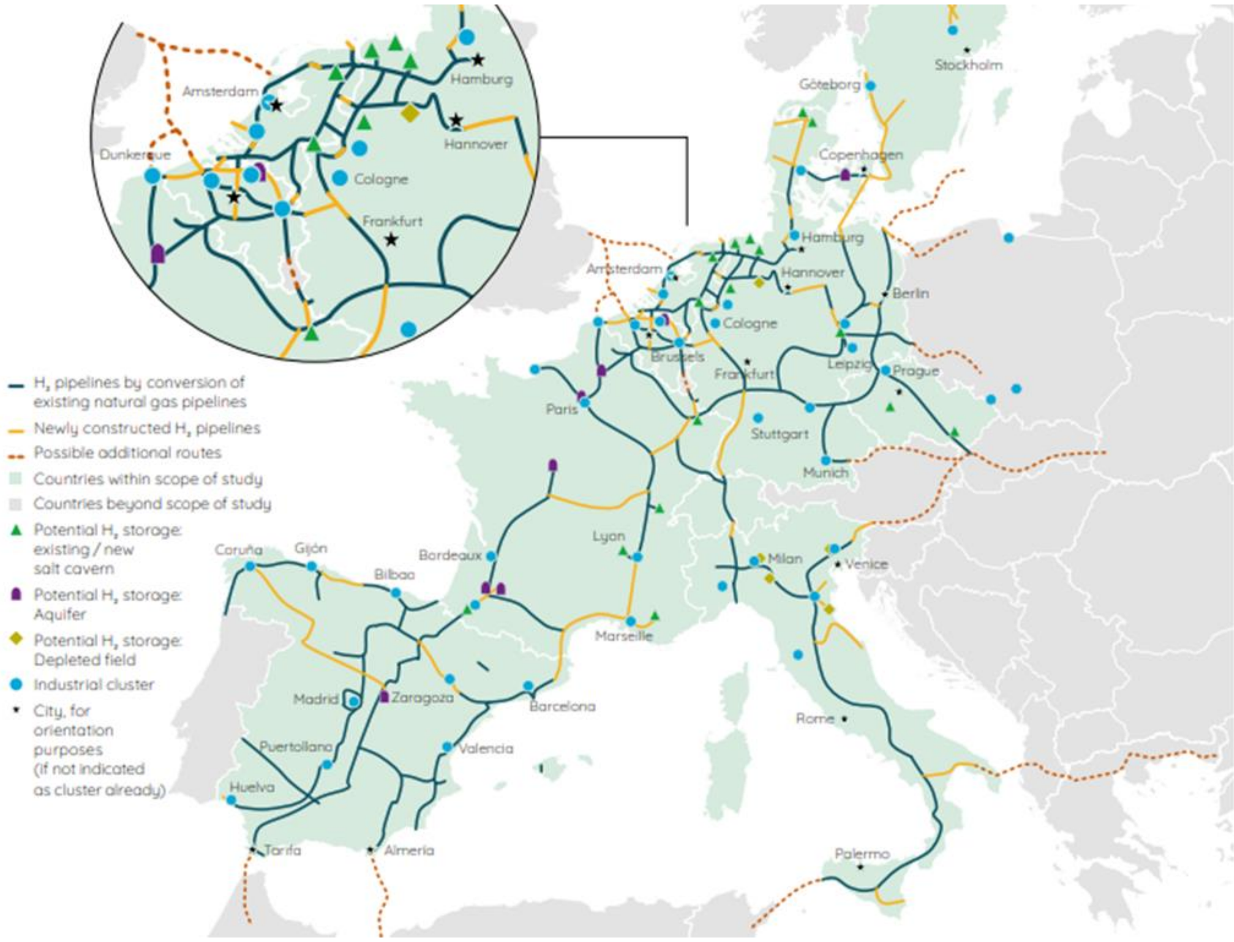


Figure 42: EU Hydrogen Backbone

Source: (Guidehouse 2020, p 8)

India advanced in extending renewable energies such as PV and wind, but does not yet have a remarkable hydrogen infrastructure. However, the Norway-based company DNV will offer technical guidance and assistance to India's Pipeline Infrastructure Limited (PIL) regarding the incorporation of blended hydrogen into its gas transmission pipelines across India. This encompasses transmission lines, interconnectors, stubs, compressor stations, valve and metering stations, and related equipment. Blending hydrogen with natural gas in existing infrastructure enables countries like India to transition towards a decarbonized future (SEI 2022).

Japan is heavily investing in hydrogen technology as a means to decarbonize its economy and maintain industrial competitiveness. The country is focusing on securing access to hydrogen feedstocks and developing a diverse hydrogen market, while also maintaining a strong position in fuel cell technology, particularly fuel cell vehicles. The Japanese government is committed to funding research, development, demonstration, and deployment, and actively collaborates with industrial stakeholders to promote the integration of hydrogen and fuel cell technology into society (CSIS 2021a).

In South Korea, Linde has partnered with Hyosung Corporation, one of South Korea's largest industrial conglomerates, to build, own and operate extensive new liquid hydrogen infrastructure. On behalf of the joint venture, Linde will build and operate Asia's largest liquid hydrogen facility. With a capacity of over 30 tons per day, this plant will process enough hydrogen to fuel 100,000 cars and save up to 130,000 tons of carbon dioxide emissions per year (LINDE 2021).

4 Saudi-Arabia's own hydrogen potential

The Paris Agreement was adopted in December 2015 under the United Nations Framework Convention on Climate Change. It aims to achieve net-zero greenhouse gas emissions by 2050 in order to limit the global temperature increase to below 1.5°C; it further urges countries to support climate mitigation policies both politically and economically. Following the Paris Agreement, policymakers have been reviewing alternative energy sources to achieve the goal of net-zero carbon emissions, and as a secondary energy source, hydrogen is becoming one of the most preferred energy carrier options. By 2021, 13 countries had announced their national strategies for hydrogen as an alternative to fossil energy sources. In the announced strategies, hydrogen is seen as the key energy carrier for a low-carbon world. The strategies provide the necessary policy support to pave the way for hydrogen as a low-carbon or even carbon-free energy source (Quamar Energy 2020); (KAPSARC 2021).

In the light of Vision 2030, the Saudi government and policymakers are developing the national hydrogen strategy focusing on the following points (Guidehouse 2022b):

1. Blue and green hydrogen production process aspects.
2. Using hydrogen for domestic uses especially in the transportation sector.
3. Supporting the hydrogen-based industries with high export potential (steel, fuels, etc).
4. The hydrogen export potential to the world

In this chapter, the question of the Kingdom’s hydrogen potential is addressed as follows:

1. Overview of renewable energy status.
2. Overview of water resources and desalination projects necessary for green hydrogen production.
3. Hydrogen and PTX production and consumption by applications.

4.1 Overview of renewable energy status in Saudi Arabia

In this section, an overview of the installed and expected renewable energy projects (solar and wind) in Saudi Arabia is provided to assess the potential for green hydrogen production based on available government statistical data.

Vision 2030 sets the plan for sustainable energy projects development. Programmed is to increase the renewable energy production capacities´ share versus the total energy production from different resources in the kingdom. This will result in CO_2 emissions´ reduce, meeting Saudi Arabia’s 2060 zero-emission target (Zohbi & AlAmri 2020). It needs to be noted that Aramco expands its climate goals, stating its ambition to reach operational net-zero emissions by 2050 already (ARAMCO 2021).

Figure 43 shows the increase in energy consumption in Saudi Arabia´ various sectors between 1990 and 2020. The industry (including electricity and heat generation), commercial and public services (including transport) have mainly led to an increase in CO_2 emissions (Figure 44).

Electricity consumption by sector, Saudi Arabia

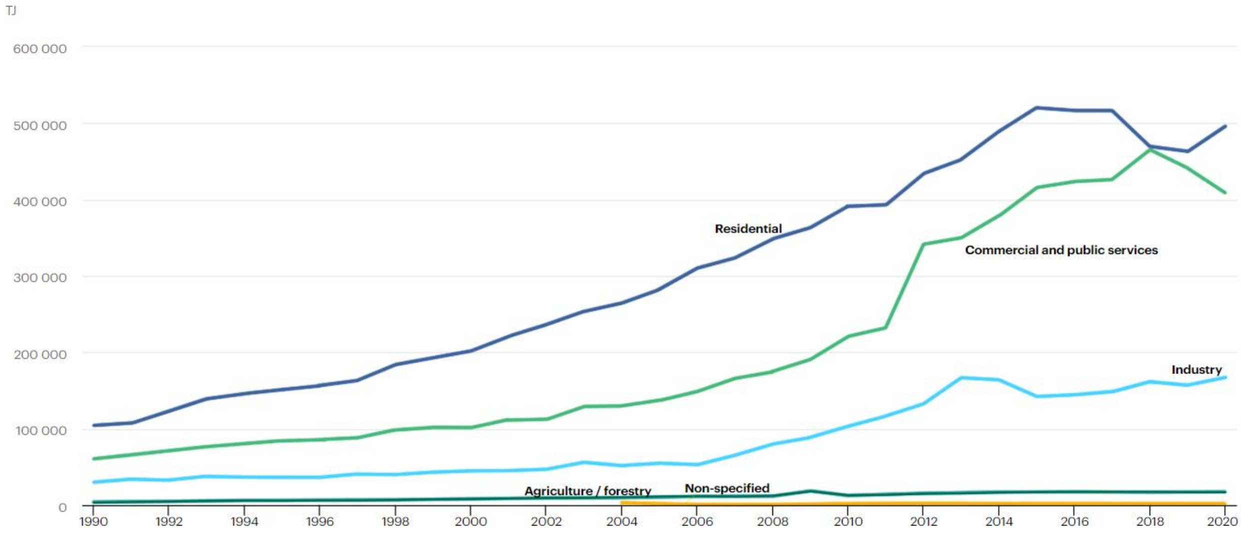


Figure 43: Electricity consumption by sector, Saudi Arabia 1990-2020

Source: (IEA 2020)

Note: 100,000 TJ are about 27.9 TWh

In Saudi Arabia, total electricity generation in 2021 was 356.6 TWh (BP 2022). As depicted in Figure 43, the residential sector is the largest consumer of electricity, followed closely by the commercial and public sector. Typically, there are two peak hours of electricity consumption per day: one at noon and the other in the afternoon after sunset. With the recent deployment of smart meters, Saudi Arabia is very advanced and well prepared for a smart grid. This is ideal for maintaining the stability of the grid, even with a high share of volatile renewable energy sources.

CO_2 emissions by sector, Saudi Arabia

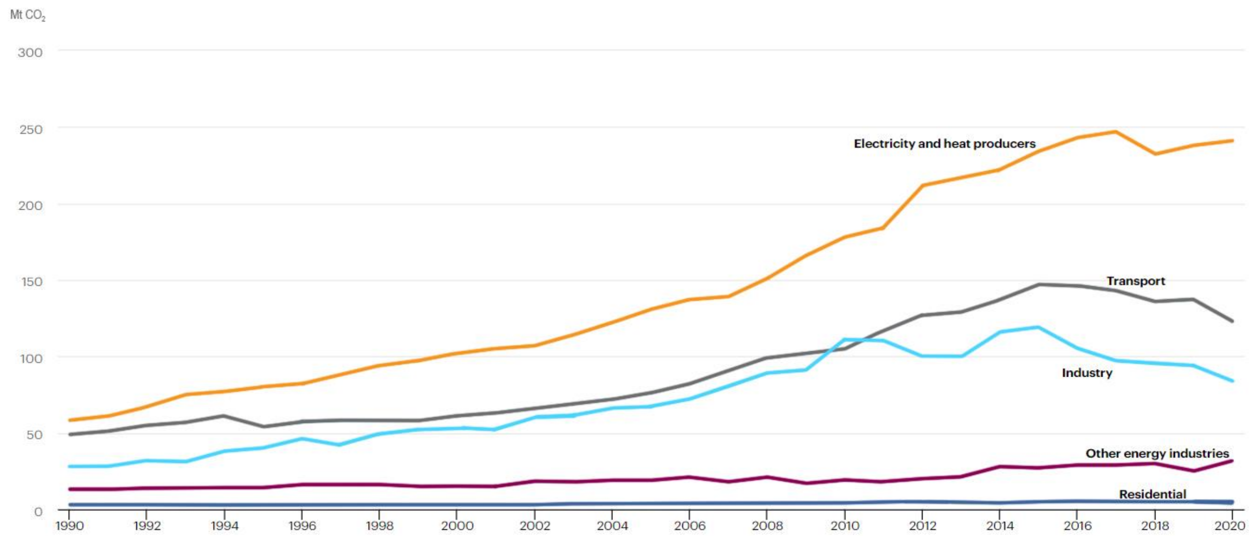


Figure 44: CO_2 emissions by sector, Saudi Arabia 1990-2020

Source: (IEA 2020)

By gradually integrating renewables into the existing conventional energy system, the goal of sustainable development is to be achieved by reducing CO_2 emissions until net zero is reached. For green hydrogen´s production, the development of renewable energy generation projects such as PV, CSP and wind turbines is a top priority to decarbonize the hydrogen production process and reduce CO_2 emissions.

4.1.1 Wind

Wind Energy Potential in Saudi Arabia

Figure 45 provides mean wind speed at 100 m height in Saudi Arabia. Several coastal areas and mountain regions in Saudi Arabia present excellent wind conditions with an average wind speed of 7.5-8 m/s on the east coast and 7-7.5 m/s on the west coast. The average wind speed in the central region is 5-6.5 m/s (AlGhamdi et al. 2022).

The wind energy potential of Saudi Arabia is estimated at 145 TWh_{el} (Guidehouse 2022b, p 3).

Mean Wind Speed at 100m height in Saudi Arabia

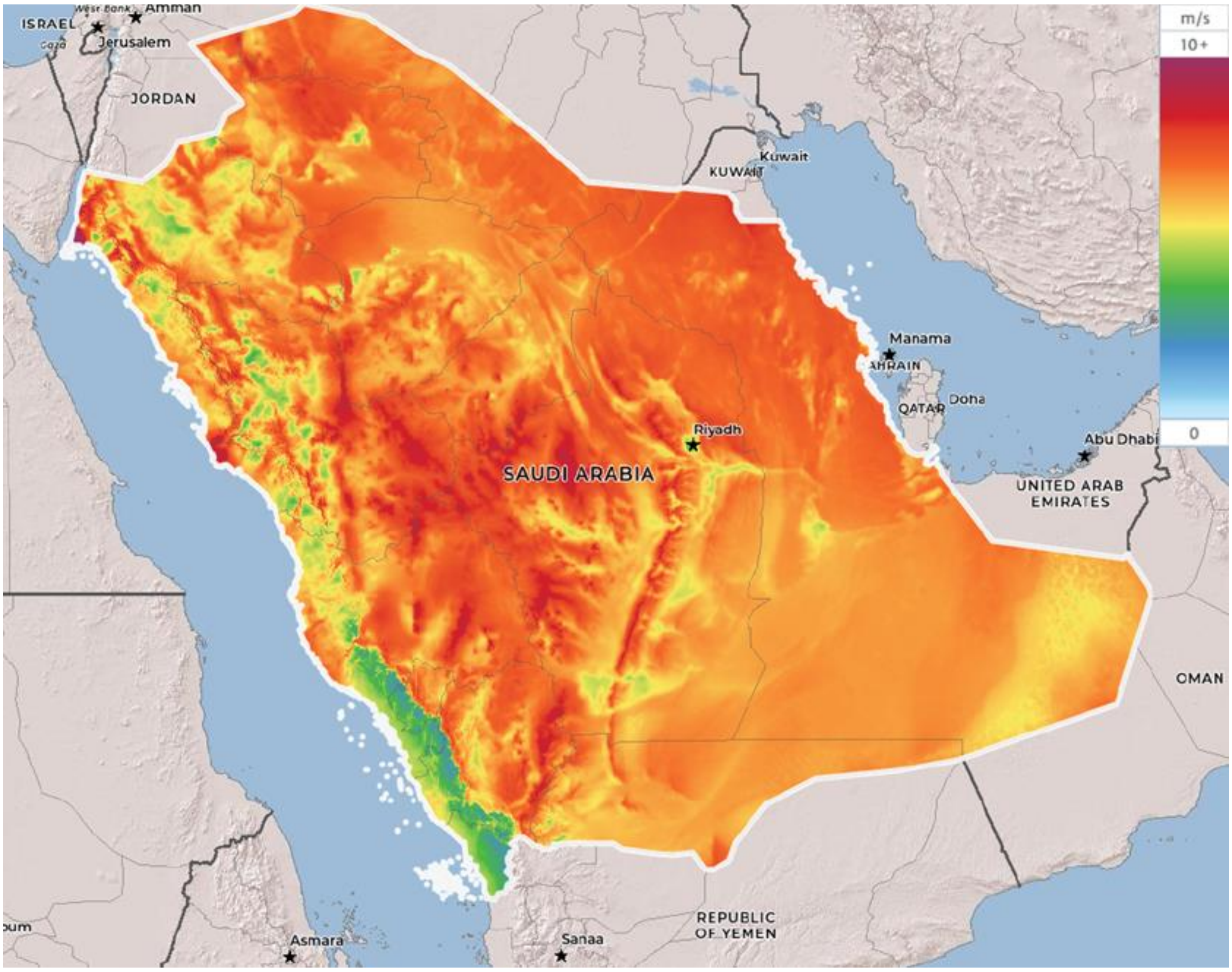


Figure 45: Mean Wind Speed at 100m height in Saudi Arabia

Source: ESMAP GLOBAL WIND ATLAS 2023, This map is printed using the Global Wind Atlas online application website (v.3.1) owned by the Technical University of Denmark. Web source https://globalwindatlas.info/

Utility-scale turbines can expect a high energy yield from wind power plants located where the annual average wind speed is at least 13 miles per hour (mph), which is equivalent to 5.8 meters per second (m/s) (EIA 2022). The web source https://globalwindatlas.info/ provides an initial overview of wind resources. Measuring the wind speed at a specific location over a longer period of time is highly recommended for a detailed analysis. Note that the wind energy increases cubically with the wind speed: doubling the wind speed results in an eightfold increase in energy yield (2 to the power of 3). If the wind speed is lower than expected, the power generation will decrease accordingly. For instance, a 50% reduction in wind speed will result in a 12.5% decrease in power generation (0.5 to the power of 3). The average wind speed remains a crucial factor in determining the amount of (electrical) energy generated by a wind turbine at a specific location.

Global weighted-average total installed costs for wind power in 2020 was $1,349/kW installed for onshore wind and $3,185/kW for offshore wind projects (IRENA 2022a, chart data Figure 1.4).

Wind Energy Installed Projects in Saudi Arabia

One wind power project is in operation since Q1-2022 in Dumat al-Jandal with an installed capacity of 400 MW.

For future planning, 3 projects are to be developed with a total wind power capacity of 1,800 MW.

4.1.2 Solar

Solar Energy Potential in Saudi Arabia

To harness new energy sources, solar power has been widely regarded as a promising resource. With an average of 8.9 hours of sunshine per day and one of the highest solar radiation intensities in the world, Saudi Arabia is a very fortunate country when it comes to sunlight, receiving an average horizontal solar radiation of 6,474 Wh/m^2/day. Almost 1,000 TWh of solar energy potential has been estimated in Saudi Arabia (Guidehouse 2022b, p 3). For fix-tilt PV systems, Figure 46 illustrates the PV power potential throughout the Kingdom of Saudi Arabia from 1999 to 2018 on daily as well as on yearly totals. Most provinces have registered high potential for solar PV, ranging from about 4.8 to over 5.5 kWh/kWp (Zohbi & AlAmri 2020). A single-axis tracking PV system, calculated with PVGIS, yields even more specific annual energy (2,600 kWh/kWp installed) compared to fix-tilt PV systems. According to these calculations, about 385 MWp of single-axis tracking PV systems installed in Saudi Arabia are sufficient to generate 1 TWh of electricity per year, assuming regular maintenance and cleaning.

PV Power Potential Saudi Arabia

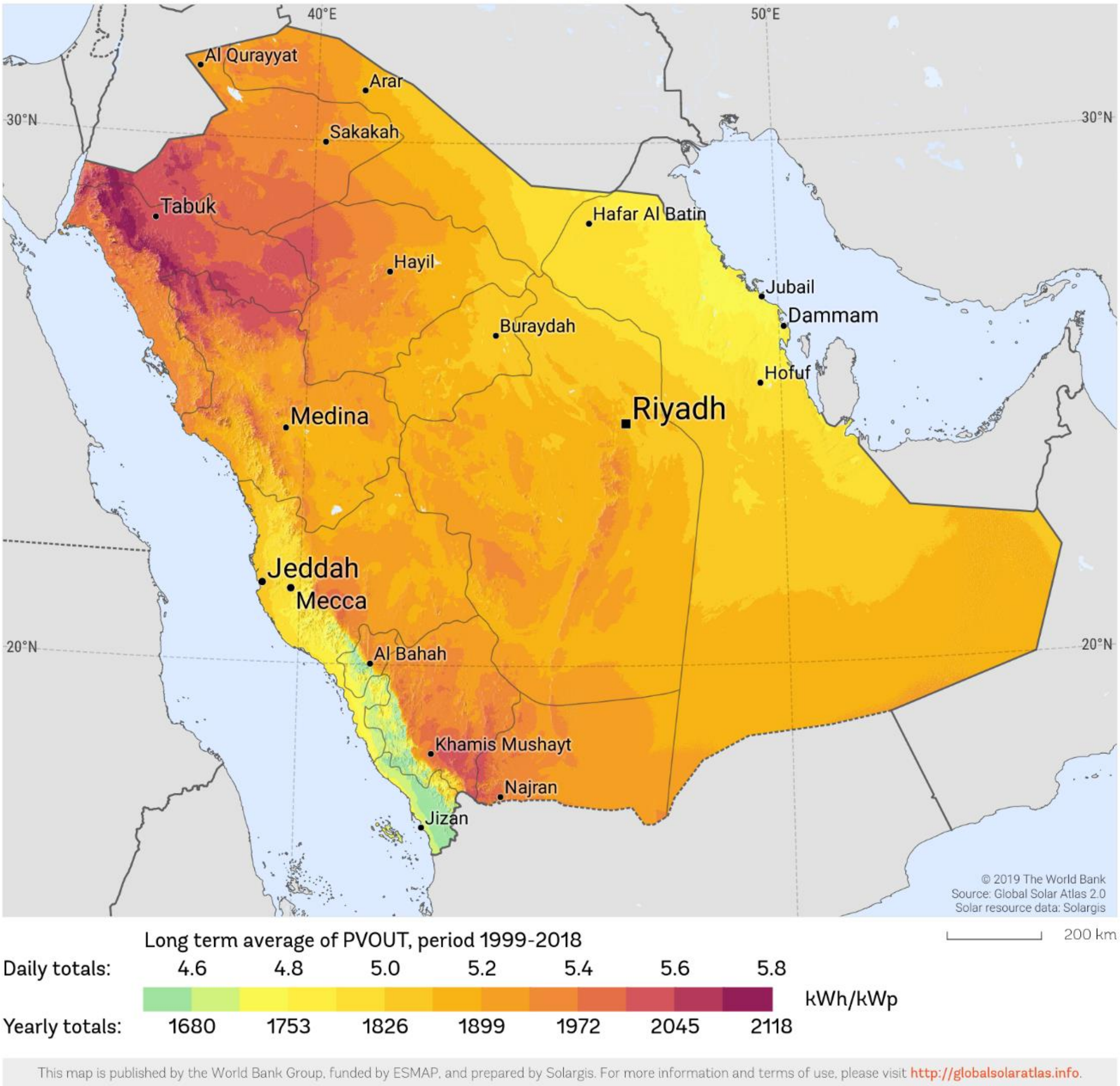


Figure 46: Photovoltaic power potential in Saudi Arabia

Source: ESMAP SOLARGIS, World Bank 2019

Solar energy installed and expected projects in Saudi Arabia

By the end of 2022, a total of 6 Solar PV systems were operational, with an installed capacity of 1,170 MW (GASTAT 2020).

In April 2023, the Middle East Solar Industry Association (MESIA) forecasted that Saudi Arabia would add 10 GW of renewable capacity between 2022 and 2027, with solar PV being the primary source. Four procurement mechanisms, namely competitive auctions, unsolicited bilateral utility contracts, corporate PPAs, and state-owned projects will drive this growth according to MESIA 2023. Table 8 below contains a comprehensive list of projects with a total capacity of approximately 9.8 GWp.

Table 8: Renewable Energy Projects in Saudi Arabia – upcoming and announced solar PV and wind projects

Project Name	Type of Project	Status	Project Capacity [MWp]
PIF – Sudair	PV IPP	Tender Phase	2,000
Red Sea	PV IPP	Development Phase	650
Neom	PV + Wind	Planned	4,000
Quiddiya	PV	Tender Phase	447
Medina	PV IPP	Bid Evaluation	50
Rafha	PV IPP	Bid Evaluation	45
Qurayyat	PV IPP	Bid Evaluation	200
Al Faisaliah	PV IPP	Bid Evaluation	600
Rabigh	PV IPP	Bid Evaluation	300
Jeddah	PV IPP	Bid Evaluation	300
Al-Rass	PV IPP	Bidding Stage	700
SAAD	PV IPP	Bidding Stage	300
Wadi ad-Dawasir	PV IPP	Bidding Stage	120
Layla	PV IPP	Bidding Stage	80
Total			**9,792**

Source: (MESIA 2021, p 35)

The total capacity of the solar and wind plants for the NEOM project located in northwest Saudi Arabia is projected to reach 4 GW. Suppliers from China and India are intended to build a battery energy storage system (BESS) and a 190 km power transmission network in addition to the wind and solar plants (Arab News 2023).

Additionally, more than 70 renewable energy parks (PV, CSP and Wind) are planned with a total investment of above $90 billion, to be financed by the private sector. PV installations are expected to reach about 12.9 GW while wind power projects will be 2.2 GW amounting in total to 15 GW according to announcements from the Ministry of Energy.

4.2 Overview of water resources & desalination projects in Saudi Arabia

Water resources in Saudi Arabia, as well as installed and announced desalination projects, are discussed in the following section to answer the question of Saudi Arabia's potential for producing hydrogen by electrolysis. The availability of water resources and renewable energy capacity in Saudi Arabia should be taken into account when evaluating the country's potential for hydrogen production as it is known that the stochiometric demand amounts to about 9 tons of water to produce 1 ton of hydrogen (ENERGYPOST.EU 2021).

The use of seawater, where possible, can be a solution to water scarcity in water-stressed regions such as Saudi Arabia. The cost of desalinating seawater using reverse osmosis (RO) is approximately $1 per cubic meter of water, which is less than 0.5% of the total cost of producing electrolytic hydrogen. Desalination requires less than 0.1% of the energy consumption of the electrolyser, while reverse osmosis requires 3-6 kWh of electricity per m^3 of water. Inland areas with limited fresh water resources can also receive water from desalination plants. For a distance of 100 km, the total cost of hydrogen would increase only marginally by about $0.05-0.06/kg H_2 due to water transportation costs.

The local population in areas without access to fresh water could also benefit from the desalination plant, which is too expensive for a local community to manage on its own. However, this is only a small part of the renewable hydrogen project. (IEA 2022b, p 83).

Dams are the primary surface water resource in Saudi Arabia. The surface runoff from the dams has been estimated at 980 million cubic meters (MCM) with an average rainfall of 60 mm in 2019. With a total capacity of 2 billion cubic meters and an annual water use of 1.6 billion cubic meters, the country has approximately 522 large and small dams. (Fanack 2021).

Water that runs off and seeps into the ground in Saudi Arabia's valleys, fans, and plains contributes to shallow aquifers and is known as **groundwater**. The rapid precipitation of runoff water is facilitated by the pronounced water voids found in these small aquifers. More than the surface water used by dams, the annual renewable groundwater is estimated to be 2.8 billion cubic meters, according to (Fanack 2021).

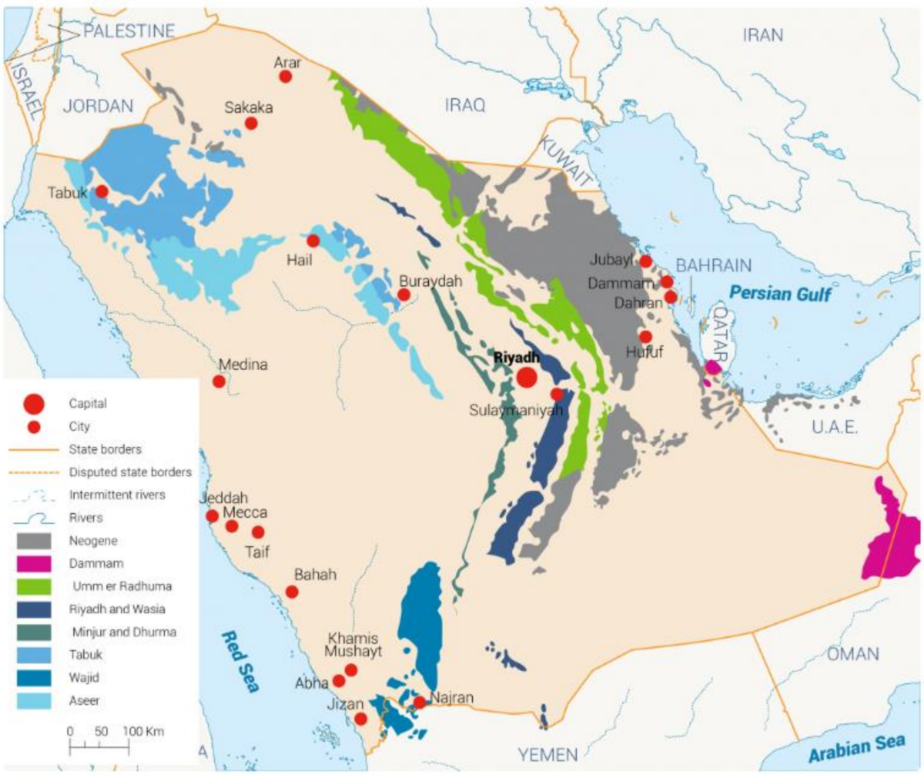


Figure 47: Saudi Arabia Groundwater Aquifers

Source: (Fanack 2021)

Major Desalination Projects

To meet the growing demand, the Kingdom created a structure for private sector participation in Independent Water and Power Projects (IWPPs) in 2002, utilizing build-own-operate and build-own-operate-transfer schemes. Three main IWPPs, namely Shuaibah III, Jubail III, and Shuqaiq II, were developed initially. Nearly 2 million people will benefit from the $600 million Shuqaiq III expansion, which is among the many desalination projects currently underway or being expanded. In September 2020, Acciona S.A., the primary contractor for Al-Khobar I desalination plant, started supplying water to 350,000 people daily. The Spanish company is responsible for the operations.

Figure 48: Al-Khobar Desalination Plant.

Source: Acciona, S.A. (U.S.-Saudi Business Council 2021b).

In 2015, the Saline Water Conversion Corporation SWCC began operations of the Ras Al-Khair desalination plant, which cost $7.2 billion and added over 1 million m^3/d to the national supply. It is a massive hybrid water desalination plant and the first of its kind built on this scale, with a 2,400 MW power plant also included in the project. In its east-coast city of Jubail, Saudi Arabia boasts another large desalination plant with an output capacity of 1.4 million m^3/d (U.S.-Saudi Business Council 2021a).

The SWCC's most recent major desalination project, Yanbu III, commenced operations in November 2020 at a cost of $1.3 billion. As an industrial city, Madinah and Yanbu, it is supplied with 550,000 m^3/d of water and 3.1GW of power generated from the hybrid power/desalination plant, benefiting 1.8 million people. A new expansion project to the Yanbu desalination facilities is being undertaken by the Saudi Water Partnership Company (SWPC), previously known as the Water and Electricity Company, which acts as a purchasing agent for the SWCC and the Saudi Electricity Company. Yanbu IV, which includes a 20 MW solar photovoltaic facility, will add 450,000 m3/d water output at a cost of $850 million. In February 2015, SWCC selected Black & Veatch as the engineering and design consultant for the Shuaibah IV desalination project, a $500 million plant capable of producing 400,000 m^3/d of drinking water. The plant is intended to supplement the city of Jeddah's drinking water supply.

ACWA Power was chosen by the Saudi Ministry of Environment, Water, and Agriculture (MEWA) to work with the Saudi Brothers Commercial Company on the development of Rabigh 3 IWP, a reverse osmosis desalination plant that has a capacity of 600,000 m^3/d (which can be expanded to 1,200,000 m^3/d). Water is provided to Jeddah, Makkah, Taif, and surrounding villages through the $600 million project. ACWA Power will own 70% of the company after completion of the project. In addition, the SWPC plans to construct Rabigh 4, which will have a capacity of 900,000 m^3/d and cost $600 million, as well as Rabigh 5, which will have a capacity of 400,000 m^3/d and cost $400 million. capacity) and Rabigh 5 (a $400 million expansion with 400,000 m^3/d capacity) (U.S.-Saudi Business Council 2021a).

Solar-Powered Desalination

Saudi Arabia is the largest country in the world without flowing surface water and has one of the highest water consumption rates. The country has relied on desalinated water since the 1950s and has become the world's leading producer of desalinated water, accounting for 22% of global production and producing 7.6 million m^3 per day. SWCC, a state-owned organization, operates 33 desalination plants at 17 sites throughout the Kingdom (as of October 2020). This represents about 69% of desalination in the Kingdom, equivalent to 5.6 million m^3/d, and 20% of desalination worldwide. Saudi Arabia is leading the way in the desalination industry with innovations in solar-powered desalination plants. Advanced Water Technology completed the world's first large-scale solar-powered desalination plant in 2018 to serve 100,000 people in Al Khafji. With new technologies and techniques, companies can help Saudi Arabia solve its water problems while saving an estimated 1.5 million barrels of oil per day. (U.S.-Saudi Business Council 2021a).

Desalination investments and initiatives

The main methods of water desalination used in Saudi Arabia are multi-stage flash, reverse osmosis, and multi-effect distillation processes. The SWCC declared its intention to spend $80 billion in 2016 to enhance the production of desalinated water. In addition to investing almost $6.7 billion in more than 300 water projects, the National Water Company anticipates billions more in investment opportunities in the years to come (U.S.-Saudi Business Council 2021a).

4.3 Hydrogen and PtX production and consumption in Saudi Arabia

The following paragraphs illustrate the status of hydrogen production (or derivatives) rate now and in the coming years and are showing the hydrogen consumption comparison between the types of hydrogen (Green – Blue – Grey).

4.3.1 Hydrogen and PtX production and demand

The key hydrogen projects in Saudi Arabia and the Arab Gulf States are herein presented.

ACWA Power, Air Products, and NEOM have formed the **NEOM Green Hydrogen Company** (NGHC) to develop a world-class large-scale green hydrogen project in Saudi Arabia. Production facilities, including a 2 GW electrolyser capacity, will be powered by 4 GW of renewable energy from solar, wind, and storage. A cost-effective solution for worldwide transportation is the future hydrogen production of 650 tons of carbon-free hydrogen per day (which is 237,250 tons per year in the form of green ammonia) which considers the project at NEOM as a preliminary stage (Guidehouse 2022b).

This project will save almost 5 Mt of CO_2 per year worldwide in comparison to diesel trucks or buses, by manufacturing and exporting green ammonia to transport hydrogen for mobility in global markets. The primary EPC contractor for the production of green ammonia is Air Products, which will also be the exclusive off-taker. The green ammonia will be transported globally and dissociated to produce green hydrogen for the transportation market. ACWA Power is planning to develop two more projects of similar scale, most likely to be located at NEOM, to cope with the growing global demand for green hydrogen.

Aramco, the Saudi Arabian Oil Company, published in June 2022 its first sustainability report, which outlines ways in which the company plans to further tackle the undesirable emissions, in the meantime delivering reliable and affordable energy solutions.

Targets are as follows according to Aramco’s annual report 2022:

- Goal to reduce upstream carbon intensity by at least 15% by 2035, against the 2018 baseline.

- Greenhouse gas emission initiatives aim to reduce or mitigate more than 50 Mt of CO_2 equivalent annually by 2035.
- Goal to capture, utilize or store 11 Mt of CO_2 equivalent annually by 2035.
- Company aims to produce 11 Mt per year of blue ammonia, a carrier of blue hydrogen, by 2030, supporting emissions reduction in hard-to-decarbonize sectors.
- Investments in renewable energies with a generation capacity of approximately 12 GW of solar and wind energy are planned by 2030.

Aramco plans to lower its upstream carbon intensity to 8.7kg of CO_2 equivalent per barrel of oil equivalent (CO_{2e}/boe) by 2035, which is a 15% reduction from its 2018 baseline of 10.2kg CO_2e/boe. This is already one of the lowest in the industry.

By 2035, the company plans to decrease or alleviate its net GHG emissions by over 50 Mt of CO_{2e} per year across all of its wholly-owned operated assets in both the upstream and downstream segments, compared to the business-as-usual projection.

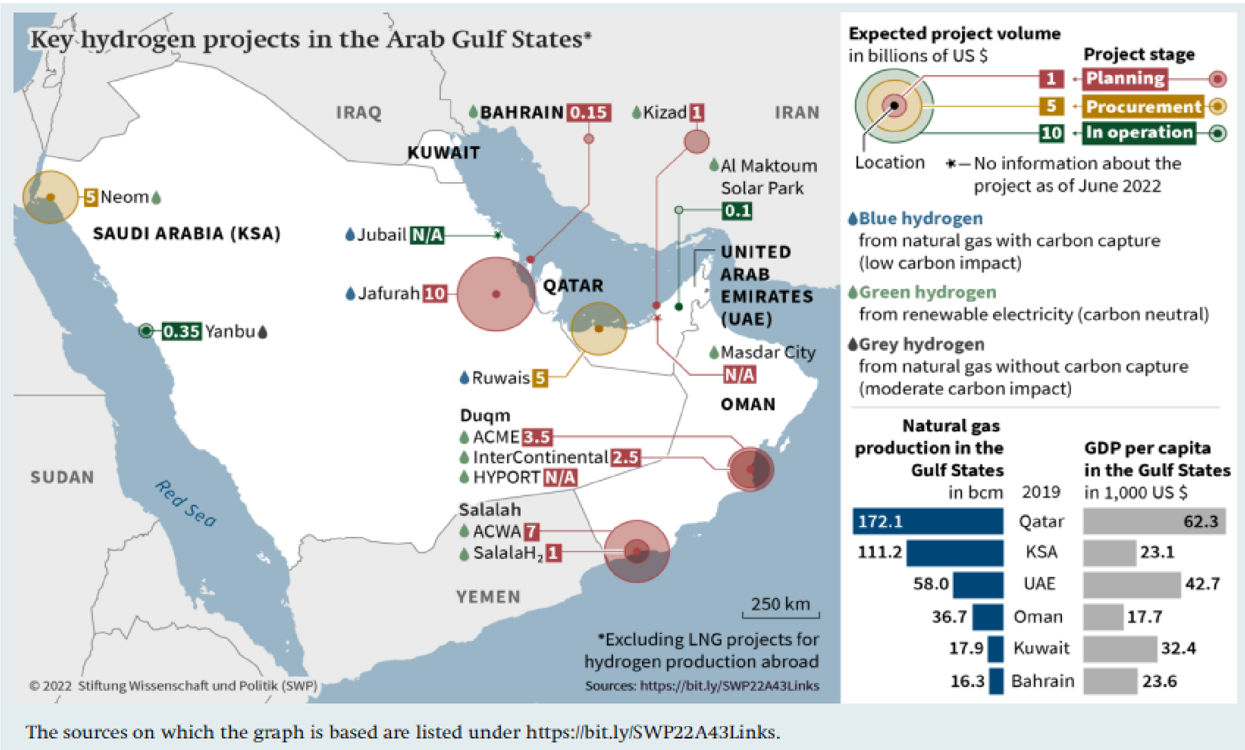


Figure 49: The hydrogen projects in the Arab Gulf States

Source: (Ansari 2022, p 4)

Global and Saudi Arabian Demand for Hydrogen

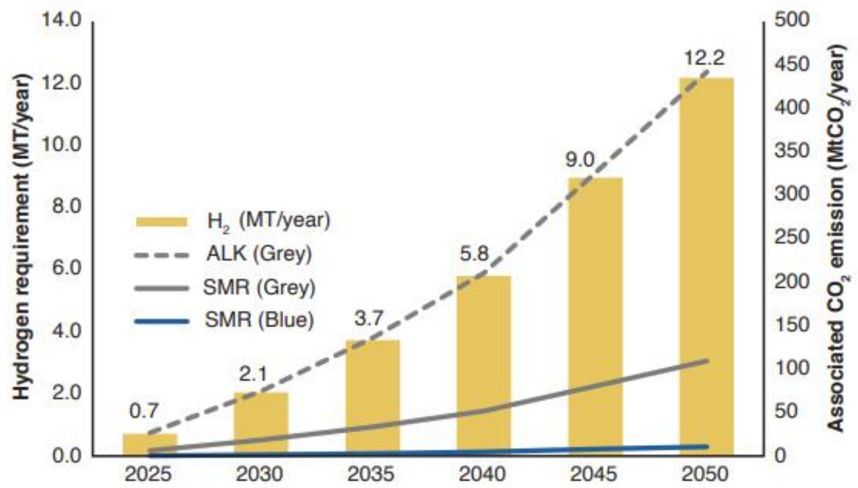
Various institutions offer a variety of hydrogen demand projections due to the growing hydrogen market. The IEA predicts that global hydrogen demand will reach 30 EJ (= 8,333.33 TWh calorific value) by 2050 in its sustainable development scenario (IEA 2020). Demand is expected to reach approximately 62 EJ (= 17,222.22 TWhcal) in the net-zero scenario (IEA 2021c).

The Hydrogen Council predicts that hydrogen demand will increase almost tenfold by 2050, reaching 78 EJ (= 21,666.67 TWhcal) in a two-degree scenario (H2C 2017, p 20). Meeting 18% of the final global energy demand across various sectors such as transportation, industrial energy, power generation, and building heat is expected.

Assuming that the Kingdom's future energy needs follow a similar trajectory, it can be estimated that by 2050, Saudi Arabia will require approximately 12 Mt of hydrogen per year to account for 18% of its total primary energy consumption. This takes into account a 2.5% yearly increase in overall final energy usage. Figure 50 shows the projected hydrogen demand and the corresponding requirements for its gradual integration into the energy mix based on these assumptions. In a green-only scenario, renewable energy resource demand is expected to rise by around 600 TWh_{el} by 2050.

Approximately 5.3 billion cubic feet (bcf) per day of natural gas in a similar blue-only scenario will be required to meet hydrogen demand in the year 2050. Green or blue hydrogen will be sufficient to meet the Kingdom's projected hydrogen demand, considering Saudi Arabia gas reserves and renewable energy potential. A lower-cost solution might be achieved by following a combination of the two paths. (KAPSARC 2021).

The Economics and Resource Potential of Hydrogen Production in Saudi Arabia



	2025	2030	2035	2040	2045	2050
H_2 as % of final energy consumption	2%	5%	8%	11%	15%	18%
Green-only						
Electricity requirement (TWh)	36	102	185	288	445	604
Associated RE capacity (GW)	16	44	80	124	192	260
Blue-only						
Natural gas requirement (bcf/day)	0.3	0.9	1.6	2.4	3.9	5.3

Figure 50: The Economics and Resource Potential of Hydrogen Production in Saudi Arabia

Source: (KAPSARC 2021, p 24)

Implemented by

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Recently, and due to pressure on the global economies to decarbonize, hydrogen is considered to be a favorable solution, for now and in future, for the hard-to-abate industries, despite being rarely used as an energy carrier for decades.

The hydrogen value chain is delineated in Figure 51, from production to current and emerging end-use applications. It also underlines the expected energy sustainability areas that could be achieved if energy generated by fossil fuel is replaced with cleaner and more flexible energy, e.g. from hydrogen.

Hydrogen Value Chain

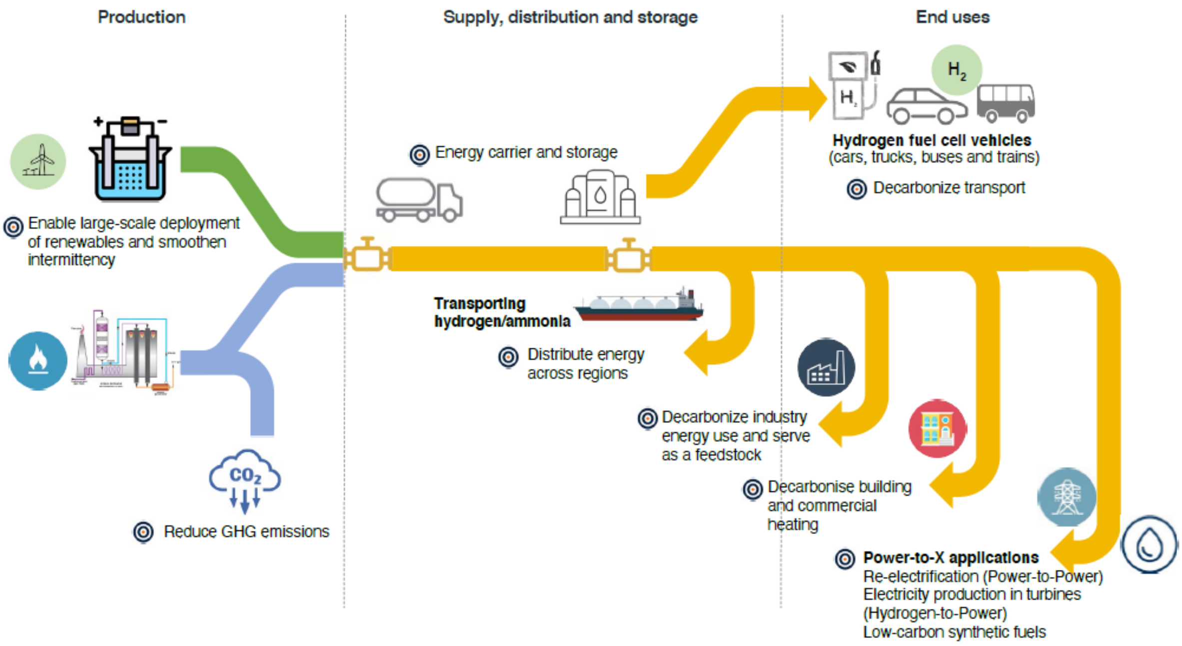


Figure 51: Hydrogen Value Chain

Source: (KAPSARC 2021)

4.3.2 Hydrogen Consumptions and Applications

By adopting hydrogen, Saudi Arabia is advancing its economic diversity plan, Saudi Vision 2030, as stated in a report of (KAPSARC 2020). Furthermore, producing and utilizing green and blue hydrogen is a priority for the Kingdom to enable the circular carbon economy (CCE). Saudi Aramco announced its inaugural hydrogen delivery from Saudi Arabia to Japan in September 2020. The first shipment of high-grade blue ammonia, weighing 40 tons and intended for use in zero-carbon power generation, marked a worldwide milestone (Ratcliffe 2020).

Saudi Aramco and Mitsubishi Corporation's partnership, which spans the entire supply chain, including the capture of associated CO_2 emissions, the conversion of hydrocarbons into hydrogen to ammonia, and the ports used for shipping ammonia. Aramco aimed to establish hydrocarbons as a reliable and cost-effective source for low-carbon hydrogen and ammonia (Arab News 2020).

Globally, hydrogen is most widely used today in the following applications (in pure or mixed form and type): oil refineries at 33%, production of ammonia and methanol at 27% and 11% respectively, and steel production with a DRI manufacturing technology at 3% (IEA 2019). The following sections provide an overview of each hydrogen demand application and estimated cost.

Oil Refinery

Refining, an energy-intensive industry, predominantly relies on hydrocarbons for steam, heat, and electricity. As the largest hydrogen-consuming sector, it obtains hydrogen mainly from oil (naphta reforming) or natural gas (steam reforming) to produce end-user products like transportation fuels and petrochemical feedstock. Refineries use 38 MtH_2/yr (33% of global hydrogen demand) for feedstock, reagent, and energy. Around two-thirds of this hydrogen comes from dedicated facilities or merchant suppliers ("on-purpose" supply). Grey hydrogen contributes to about 20% of refinery emissions, totaling 230 $MtCO_2$/yr. With tightening sulfur content regulations, refinery hydrogen demand is likely to increase, providing an opportunity for cleaner hydrogen pathways to reduce emissions from transportation fuels (IEA 2019).

Globally, less than 1% of the demand for hydrogen is currently met from clean sources, that is, either by hydrogen produced via electrolysis utilizing RE electricity (green hydrogen) or from fossil fuels with carbon capture technologies applied (blue hydrogen). Only a few refineries in North America, Europe and China can currently produce low-carbon hydrogen on a commercial scale. However, at least 25 other refinery projects are in the pipeline at various stages of development, and many more are being implemented as part of decarbonization strategies. The refining sector is a small but significant contributor to greenhouse gas (GHG) emissions in many markets, and plans are being put in place to further incentivize the use of clean hydrogen to displace fossil fuels currently used in combustion (fitchsolutions.com March 2023 - ISSN: 1750-7502)

The major hydrogen-consuming processes in the refinery are hydrotreating and hydrocracking. Hydrotreatment is used to remove impurities, particularly sulfur (it is often simply referred to as hydrodesulfurization or simply desulfurization), and accounts for a significant portion of global refinery hydrogen use. Currently, refineries remove about 70% of the naturally occurring sulfur from crude oil. As public concern about air quality grows, there is increasing regulatory pressure to reduce the amount of sulfur in finished products. (IEA 2019).

Nevertheless, multiple adoption barriers are foreseen to restrict the expansion of low-carbon hydrogen over the coming decade.

Technically, it is relatively easy to switch from grey or brown hydrogen to blue or green, as they are direct substitutes. In practice, this is likely to happen only under certain conditions. Much of the hydrogen currently used in refineries is itself a by-product of the refining process, and as such will be more difficult to displace with low-carbon supplies than hydrogen that is either produced in dedicated on-site facilities or purchased from third parties.

Even assuming that all announced projects come online as planned, it is likely that less than 5% of total refinery demand could be met by low-carbon hydrogen by the end of the decade. Saudi Arabia ranked number 7 among other countries in ammonia production at 4,499.2 thousand metric tons in 2019 (NationMaster 2023) as shown Figure 56. At least 178 kg of hydrogen is needed to produce 1 ton of green ammonia (see related box in the APPENDIX).

Methanol production data were not available, but export from Saudi Arabia was 4,538,438 tons in 2020 according to UNTradeMap data. At least 189 kg of hydrogen is needed to produce 1 ton of green methanol (see related box in the APPENDIX).

The following Figure 52 indicates that in 2017 the total refinery capacity of Saudi Aramco facilities reaches 2.9 billion barrels per year (which is about 148 Mtoe per year), which needs approximately 3 to 6 m^3 of hydrogen per barrel with total consumptions of 6 billion m^3 of hydrogen per year.

The OPEC+ kingpin added 400,000 b/d of refining capacity in 2021, due to the addition of 400,000 b/d Jizan refinery, raising the Kingdom's total capacity to refine crude oil to 3.327 million b/d, which requires approximately from 3 to 6 m3 of hydrogen per barrel with a total consumption of 19.92 billion m3 of hydrogen per year, which is about 1.7 million tons per year (S&P 2022).

In addition, Figure 52 provides a compilation of various sources that add up to a total of 3.7 million b/d of oil refining capacity in Saudi Arabia, or 189.1 million metric tons per year. Some of these are planned expansions, and there is no certainty that all refineries are operating at full capacity.

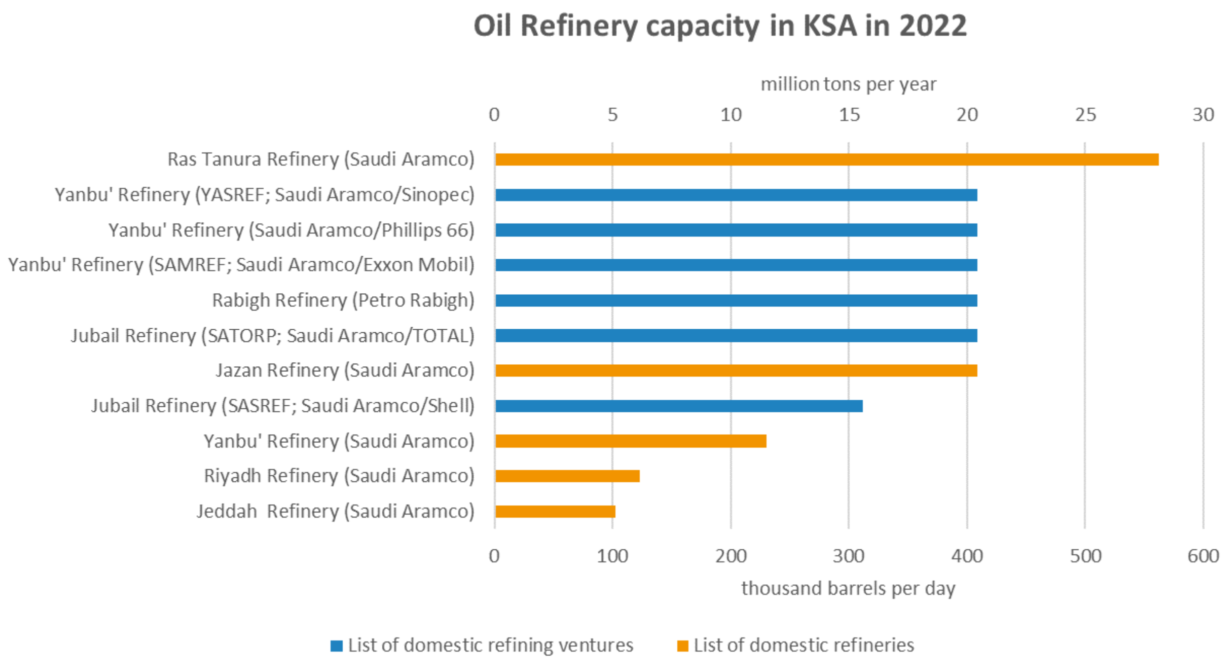


Figure 52: Saudi Aramco's refining capacity in Saudi Arabia in 2022

Sources: (LIQUISEARCH n.d.), Saudi Aramco

Ras Tanura is Saudi Aramco's largest refinery and the biggest in the Middle East. The complex processes both crude oil and gas condensates and has a natural gas liquids (NGL) processing facility and a crude stabilization facility. It is owned by Saudi Aramco and has a capacity of 550,000 barrels per day which corresponds to about 28 million tons of oil processed per annum.

Chemical and Petrochemical Industries

Worldwide, more than 32 MtH_2/yr of hydrogen is used as feedstock for the production of ammonia and more than 13 MtH_2/yr of hydrogen is used for the production of methanol. A further 2 MtH_2/yr is consumed in comparatively low volume processes (e.g. hydrogen peroxide and cyclohexane production), but most of this is supplied as by-product hydrogen generated within the sector (IEA 2019). Thus, the chemical sector is the second and third largest source of hydrogen demand directly after oil refining, as shown in Figure 53. Other minor applications bring its total demand to about 30 MtH2/yr, or 40% of total hydrogen demand in both pure and mixed forms. It is also a significant producer of by-product hydrogen, both used within the sector and distributed for use elsewhere. Most of the hydrogen consumed by the chemical industry is produced using fossil fuels, resulting in significant greenhouse gas emissions. Reducing emissions is a major challenge for the sector's energy sustainability, as well as a significant opportunity for the use of low-carbon hydrogen.

Global annual demand for hydrogen since 1975

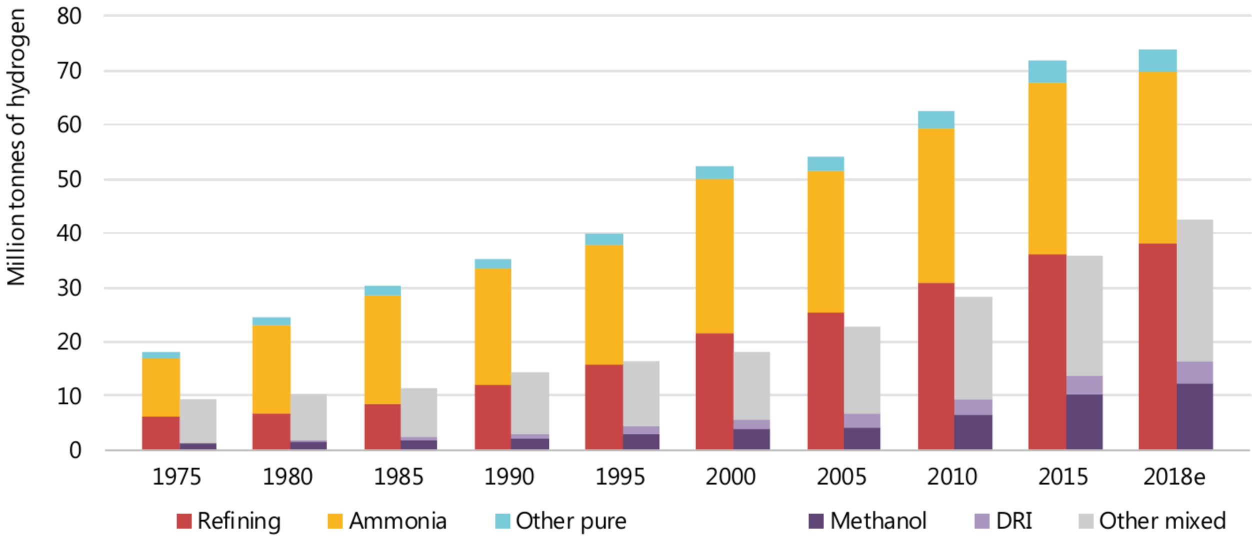


Figure 53: Global annual demand for hydrogen since 1975

Source: (IEA 2019, p 18)

Notes: DRI = direct reduced iron steel production. Refining, ammonia and "other pure" represent the demand for specific applications that require hydrogen with only small levels of additives or contaminants tolerated. Methanol, DRI and "other mixed" represent the demand for applications that use hydrogen as part of a mixture of gases, such as synthesis gas, for fuel or feedstock.

The chemical industry produces a wide range of products, from plastics and fertilizers to solvents and explosives. This section focuses on ammonia and methanol, which account for about one-third of the chemical sector's energy consumption and most of its demand for energy products as feedstocks. Although hydrogen is present in almost all industrial chemicals, only a few primary chemicals, notably ammonia and methanol, require large amounts of dedicated hydrogen production for use as feedstock (Figure 54). As depicted in Table 13 and compared with Figure 54, Saudi Arabia has a significant share of hydrogen used for ammonia and methanol production in the Middle East region.

Hydrogen demand for ammonia and methanol production in 2018

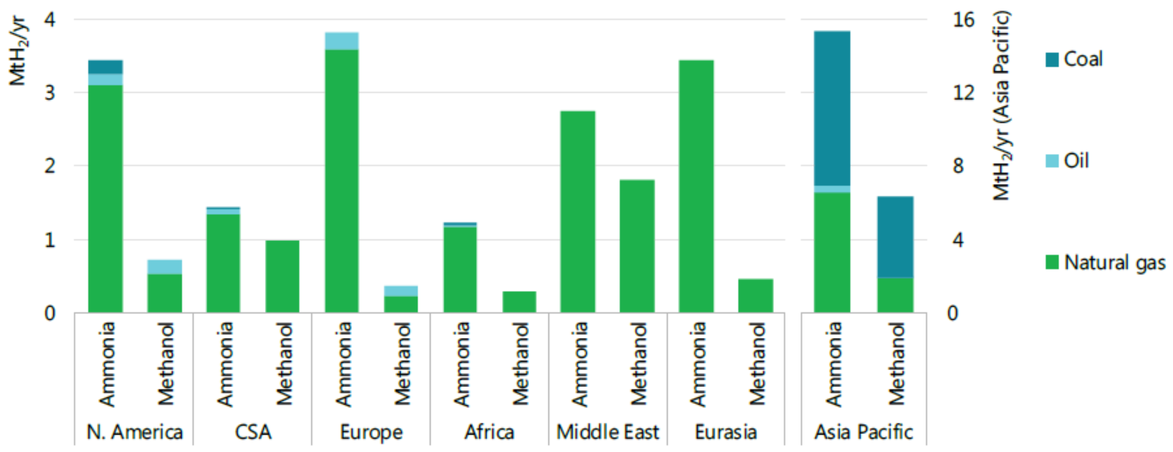


Figure 54 Hydrogen demand for ammonia and methanol production in 2018

Source: (IEA 2019)

As global demand for ammonia and methanol increases, demand for hydrogen for primary chemical production is expected to increase from 44 Mt/yr in 2018 to 57 Mt/yr in 2030, as shown in Figure 55. Ammonia demand for existing applications is expected to grow by 1.7% per year between 2018 and 2030 and continue to grow thereafter. Demand for industrial applications grows faster during this period, while demand for nitrogen-based fertilizers is expected to plateau or even decline in many regions after 2030. Methanol demand for existing applications is expected to grow at an annual rate of 3.6% between 2018 and 2030. Demand for methanol-to-olefins/methanol-to-aromatics is growing faster than total demand, at 4.1% per year over the same period, with almost all this growth coming from China. At this rate of growth, methanol production for these existing applications would require 19 MtH_2/yr by 2030, up from 12 MtH_2/yr today (IEA 2019).

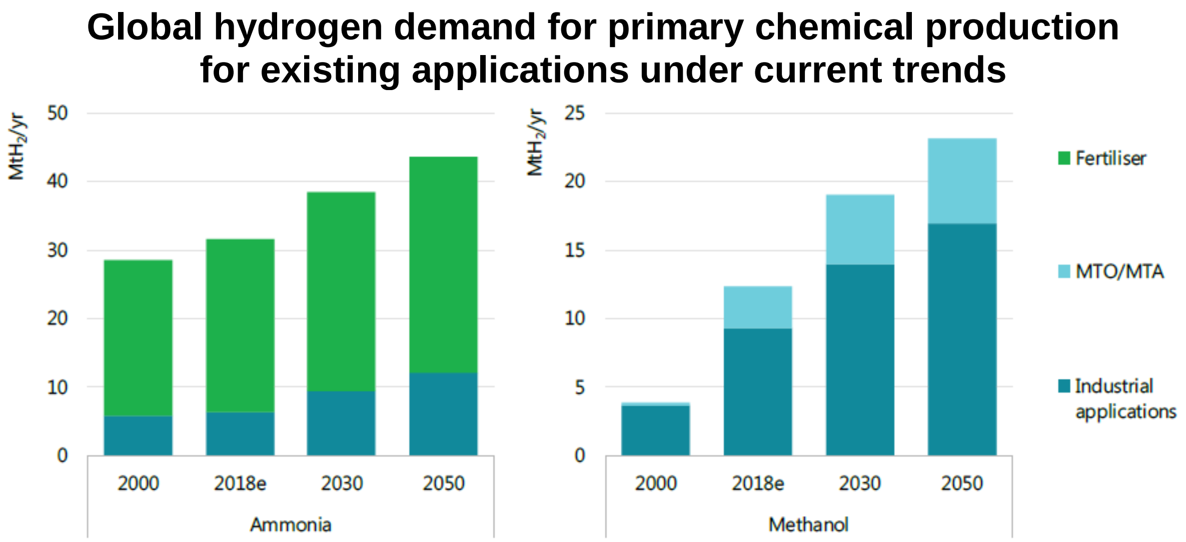


Figure 55 Global hydrogen demand for primary chemical production for existing applications under current trends
Source: (IEA 2019)
Note: MTO = methanol-to-olefins; MTA = methanol-to-aromatics

Ammonia

Saudi Arabia is targeting hydrogen production of 2.9 million tons per year by 2030 and 4 million tons per year by 2035, corresponding to around 15-20 Mt of ammonia respectively (AMMONIA ENERGY ASSOCIATION 2021). The following Figure 56 is indicating the gradual increase in ammonia production status in Saudi Arabia between 1998 and 2019.

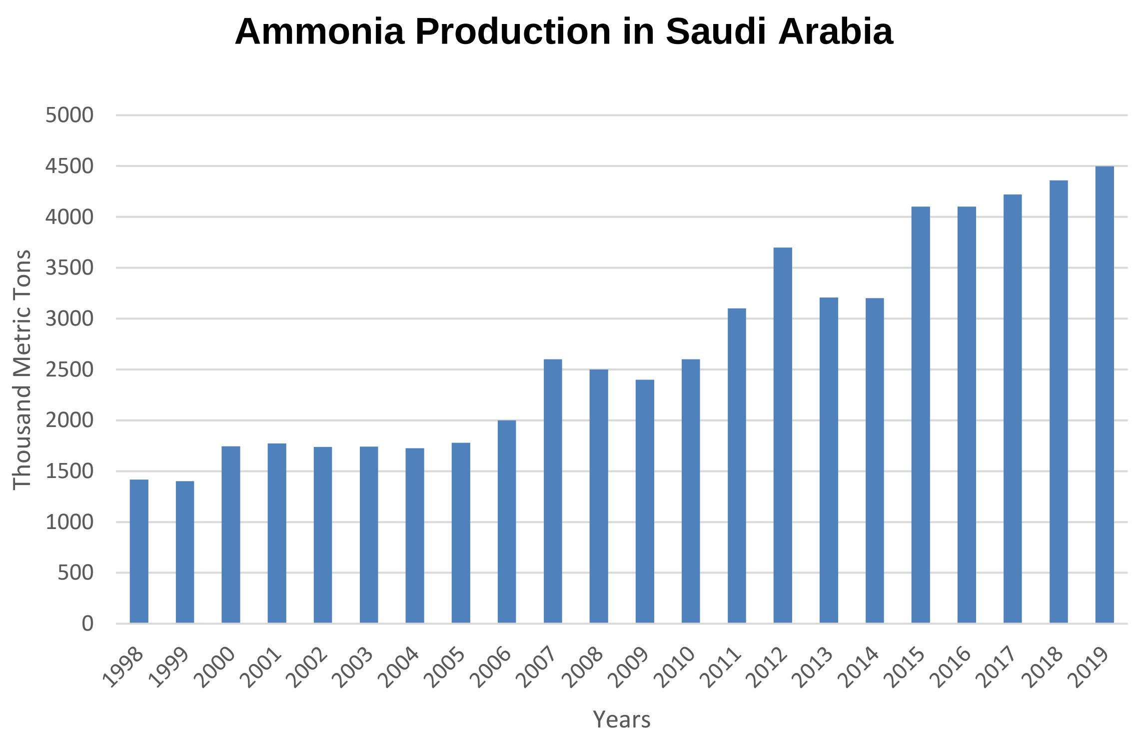


Figure 56: Ammonia Production in Saudi Arabia
Source: U.S. Geological Survey, (NationMaster 2023); Graph: ECG

The production and pilot shipment of 40 tons of blue ammonia by Saudi Aramco and SABIC utilizes and connects existing infrastructure and leverages the nearby industrial hubs and ports of Jubail in the Kingdom's Eastern Province. The Saudi Arabian Fertilizer Company (SAFCO), a SABIC affiliate, operates five ammonia plants in Jubail, with a total capacity of about 3.6 Mtpa. SABIC also operates the world's largest CO_2 purification and liquefaction plant capable of purifying 500,000 tons of raw CO_2 for such uses as methanol and urea production. As shown in Figure 57, natural gas is transported from the oil and gas fields to Jubail after being processed, where it is used as a feedstock to produce hydrogen by steam methane reforming (SMR), which then produces ammonia.

The center in Jubail Industrial City will start carbon capture and utilization (CCUS) operation by 2027 and be able to extract and store 9 Mtpa of CO_2 in its first phase, supporting Saudi Arabia's aim to extract, use and store 44 Mtpa of CO_2 by 2035. Two pilot projects for CCUS led by KAUST, NEOM and SEC; Alsafwa Cement Company, and Abdullah Hashim Industrial Gases & Equipment have been launched. Ma'aden and Gulf Cryo also announced an agreement to enhance the implementation of the circular carbon economy framework and reduce emissions. (ZAWYA 2022).

SMR is, to date, the most cost-effective way of producing hydrogen as shown in Figure 14 on page 28. However, the process is energy and carbon intensive. In the case of the blue ammonia project, about 50 tons of CO_2 is captured, 30 tons of which is utilized in SABIC's Ibn-Sina methanol plant. The remaining 20 tons are transported and injected into the Uthmaniyah oil field. The ammonia is then shipped to Japan to generate power at various production sites: the 50 kilowatt (kW) micro gas turbine site in Koriyama, the 2 MW plant in Yokohama, where the ammonia is co-fired with natural gas, and a plant in Aioi where it is co-fired with coal.

Schematic of the blue ammonia project and its value chain

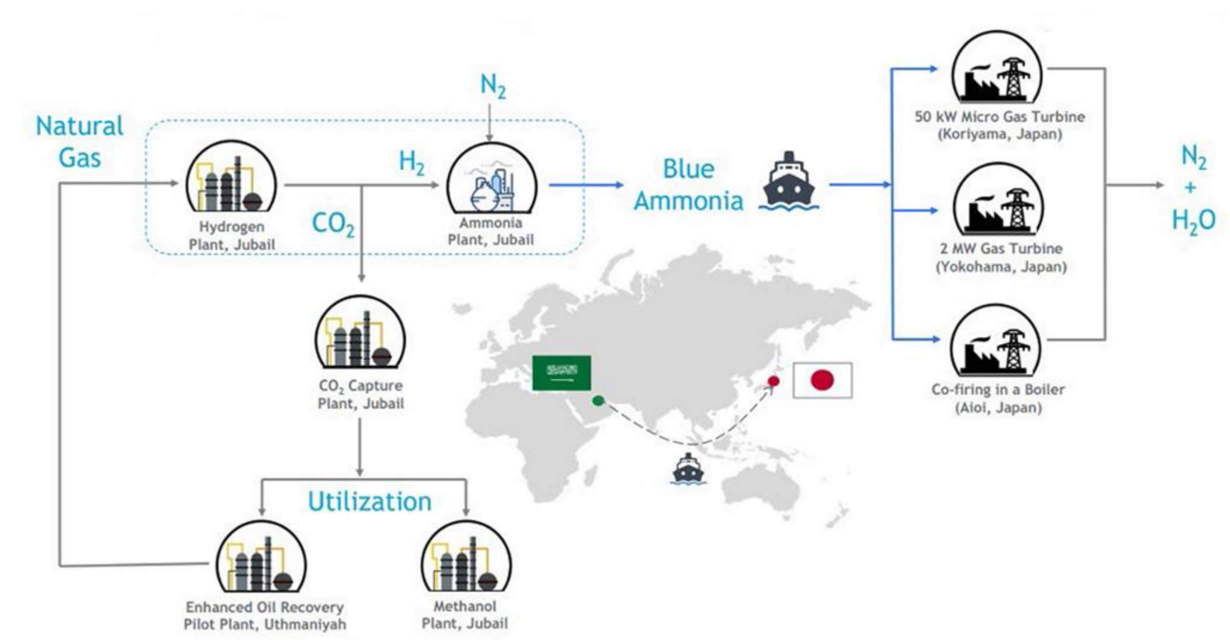


Figure 57: Schematic of the blue ammonia project and its value chain

Source: (KAPSARC 2020, p 4)

Both Neom and Saudi Aramco have selected ammonia as their hydrogen carrier of choice for the many advantages that ammonia provides for long-distance shipping. Ammonia plants are the second-largest users of hydrogen after refineries, and ammonia is the precursor for nitrogen-based fertilizers. Ammonia has an extensive and established supply chain, including above-ground storage and shipping options, and 50% higher energy density than liquid hydrogen, making it cost-efficient to transport. Neom plans to produce 650 tons of green hydrogen per day, which will feed a 1.2 Mt per year ammonia plant (AIR PRODUCTS 2020). Air Products, the exclusive off-taker of green ammonia, plans to ship it to markets in Europe and Asia, where it will be decomposed back to hydrogen (and nitrogen) and distributed to end users in the mobility sector. However, the Japanese partners in Aramco's and SABIC's blue ammonia project plan to use the ammonia directly.

Methanol

Saudi Arabia's methanol market demand stood at 3.60 Mtpa in 2020 and is forecast to reach 5.53 Mtpa by 2030, growing at a healthy CAGR of 3.94% until 2030 (CHEMANALYST 2021b).

Since methanol offers a low evaporation rate and low radiant heat, the demand for methanol in Saudi Arabia is increasing across various industries as a safer process fuel for the environment. As methanol is easily biodegradable, it is preferred as an ultimate replacement for petrochemical derivatives across various end-use industries such as chemical and petrochemical, paints and coatings, automotive, construction, etc.

Moreover, the versatile and cost-effective production routes of methanol offer an advantage over other crude oil/fuel alternatives, thereby offering high growth prospects over the forecast period. (CHEMANALYST 2021a).

The AR-RAZI Saudi Methanol Company in Al-Jubail petrochemical complex started commercial operations in 1983 and currently has an active annual capacity of 4.85 million tons per year. Its capacity is expected to remain the same in 2030 (OFFSHORE TECHNOLOGY 2021).

Table 9: Methanol plant locations and production capacities in Saudi Arabia

Ar-Razi Methanol Plant No.	Built	Production capacity [thousand tons/yr]
Ar-Razi No. 1 Methanol Plant	1983	750
Ar-Razi No. 2 Methanol Plant	1991	750
Ar-Razi No. 3 Methanol Plant	1997	850
Ar-Razi No. 4 Methanol Plant	1999	850
Ar-Razi No. 5 Methanol Plant	2008	1,650
		4,850

Source: (MGC 2019)

Saudi Arabian chemical producer Chemanol had announced plans to expand its methanol plant to increase its annual production capacity from 231,000 tons to 331,000 tons. An agreement for the basic engineering design of the plant was signed in January 2020. The additional 100,000 tons of production will be used as feedstock for future initiatives, including a dimethyl disulfide plant and a methyl diethanolamine plant, in line with Saudi Vision 2030 (Arab News 2022). Engineering design for the expansion is expected to be completed by the end of the first quarter of 2023.

Steel Production

Saudi Arabia is looking forward to "cleaning the steel industry" by using hydrogen as an energy alternative to produce "green steel" based on the lowest recorded level of emissions, contributing to the fight against climate change and achieving the Kingdom's goal of zero emissions by 2060.

The Kingdom is in a strong position to become a future pole for clean energy in the iron and steel industry, partly due to its potential ability to produce green hydrogen, as it diversifies energy sources in the steel sector to meet the needs of establishing new green local industries within the framework of Saudi Vision 2030. (The Global "Cole Nitche" Website).

DRI is a process for making steel from iron ore. Hydrogen as a reductant substitute can produce directly reduced iron (DRI), which can then be converted to steel in an electric arc furnace (EAF). Natural gas is currently used as a reductant in this DRI or EAF pathway by industries in Saudi Arabia.

After oil refining, ammonia and methanol, this process is now the fourth largest single source of global hydrogen demand (4 MtH_2/year, or about 3% of total hydrogen used in both pure and mixed forms). Global steel demand is expected to grow by about 6% by 2030, with infrastructure needs and population growth in developing regions offsetting declines elsewhere. The iron and steel sector, like the chemical sector, produces a large amount of hydrogen as a by-product mixed with other gases (e.g. coke oven gas), some of which is consumed within the sector and some of which is distributed for use elsewhere. Almost all of this hydrogen is produced using coal and other fossil fuels.

To reduce emissions, efforts are being made to test steel production using hydrogen as the primary reduction agent (rather than carbon monoxide, which is derived from fossil fuels), with the first commercial-scale designs expected in the 2030s. Meanwhile, low-carbon hydrogen could be blended into existing natural gas and coal-based processes to reduce their overall CO_2 intensity. (IEA 2019).

It is worth noting that each ton of "new" steel has typically required about 6 MWh in the process of getting from iron ore to a finished steel product.

There are 41 steel mills **in Saudi Arabia** with different capacities, categories and production processes. The demand for steel is between 14 and 15 million tons per year, while the production capacity is about 18 million tons per year. The production of crude steel in the Kingdom is more than 8 million tons per year. The following Table 10 shows the largest iron/steel producing companies in Saudi Arabia. Only one company, which is the largest, uses the DRI process method as the primary production method in the production of iron and steel.

Table 10: Steel manufacturing plants - locations and production capacities in Saudi Arabia

Serial	Company	Location	Production Method	Annual Production in Metric Tons	Steel Products
1	HADEED (SABIC)	Al-Jubail	DRI-EAF (primary)	6 Million (10 Mio. in 2025)	Rods, Re-bars, Flat/sheet plates
2	Watania Steel	Al-Riyadh	EAF (secondary)	450’000	Re-bars, billets(blocks)
3	Yamamah Steel	Yanbu	EAF (secondary)	700’000	Re-bars
4	Riyadh Steel	Al-Riyadh	EAF (secondary)	100’000	Rods, Re-bars
5	Al-Rajhi Steel	Al-Kharj	EAF (secondary)	100’000	Re-bars
6	Rabigh Steel	Rabigh	EAF (secondary)	100’000	Re-bars, billets(blocks)

Source: Steel manufacturing company’s websites

Today, primary production methods that convert iron ore into steel meet more than three-quarters of the world's steel demand, as opposed to secondary production methods that rely on limited supplies of recycled scrap steel (Figure 58). The two main primary production routes already involve some hydrogen production and consumption.

Hydrogen consumption and production in the iron and steel sector

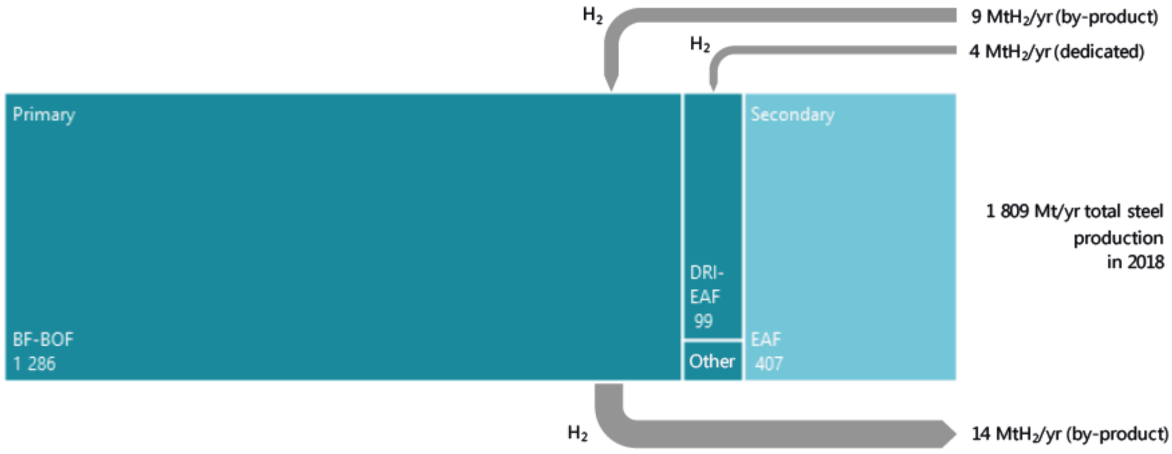


Figure 58: Hydrogen consumption and production in the iron and steel sector

Source: (IEA 2019)

Approximately 90% of the world's primary steel production comes from the Blast Furnace-Basic Oxygen Furnace (BF-BOF) route, which produces hydrogen as a by-product of coal combustion. This hydrogen, found in "works-arising gases" (WAG), reacts with gases such as carbon monoxide. WAG is used on-site and transferred to other industries for purposes such as power generation and methanol production. The iron and steel industry consumes an estimated 9 MtH$_2$/yr, accounting for about 20% of the world's mixed hydrogen consumption. BF-BOF technology is not used in Saudi Arabia (IEA 2019).

Direct Reduction Electric Arc Furnace (DRI-EAF) accounts for 7% of the world's primary steel production. It uses a mixture of hydrogen and carbon monoxide as the reducing agent. The hydrogen is produced in dedicated plants rather than as a by-product. Three-quarters of it is produced using natural gas (reforming), with the remainder produced using coal (gasification). In 2018, it accounted for approximately 4 MtH$_2$/yr, or 10% of global mixed form hydrogen consumption (IEA 2019). In Saudi Arabia, all steel producers use DRI & EAF technologies, either both (e.g. Hadeed plant) or EAF only (all other plants). It is worth mentioning that the Saudi Iron and Steel Company (Hadeed) has an ambitious plan to reach an annual steel production of 10 million tons by 2025.

Hydrogen can be used in steelmaking in two ways: either as an auxiliary reducing agent in the BF-BOF route (H_2-BF) or as the sole reducing agent in a process known as direct reduction of iron or DRI (H_2-DRI).

In the near future, methanol will also be used in the iron and steel industry as a hydrogen and carbon carrier in the fossil-free production of iron plants using the direct reduction process.

Therefore, the opportunities for using green hydrogen within the manufacturing DR technology at the Hadeed plant are very high and very encouraging.

Figure 59 indicates the steel production in Saudi Arabia between 2014 and 2021 in thousand tons annually.

Steel Production in Saudi Arabia (in Mt)

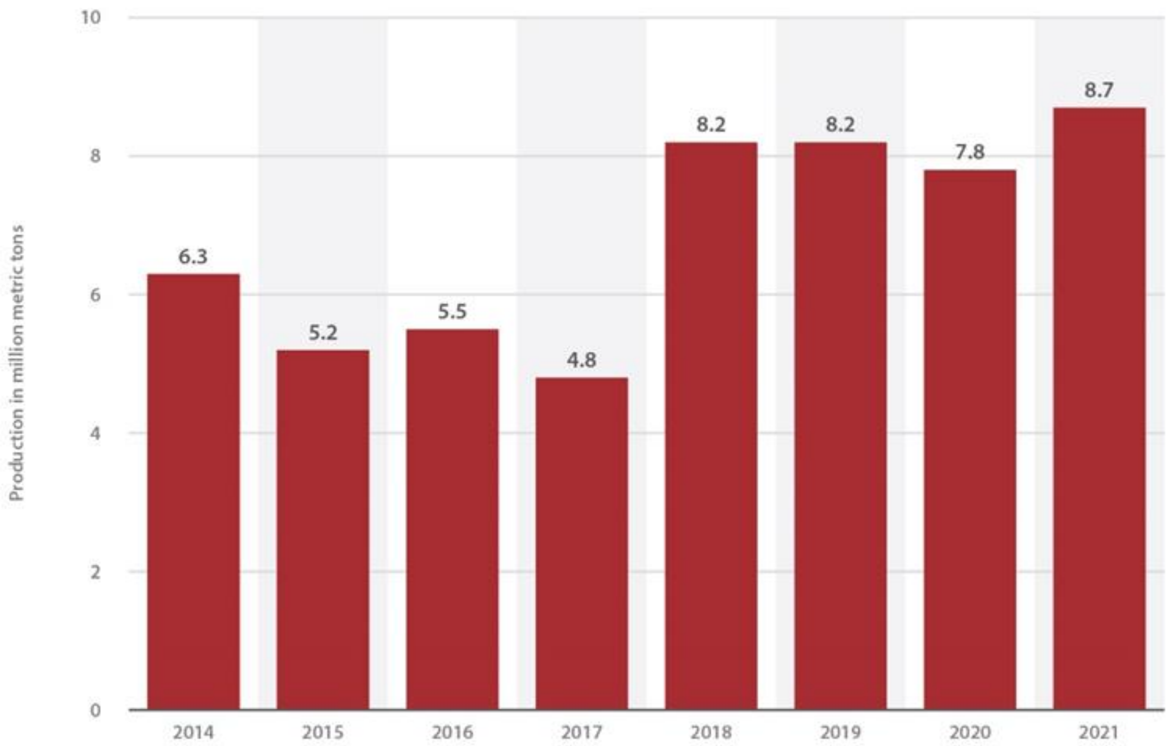


Figure 59: Steel Production in Saudi Arabia

Source: Saudi Arabia Steel Production 2022-2023 | Take-profit.org

Approximately 60 kg of hydrogen is required to produce one ton of steel (Bhaskar, Assadi & Somehsaraei 2021). Consequently, the steel industry in Saudi Arabia, especially the Hadeed plant, is expected to require approximately 600,000 tons of hydrogen by 2025.

Cement Production

Cement factories in Saudi Arabia are also a targeted consumer of green hydrogen and its derivatives as a carbon-free fuel to replace the fossil fuels currently used as the main heating source.

There are 17 cement manufacturing companies in Saudi Arabia with a total annual production of over 55 million tons. The major cement companies are listed in Table 11 below:

Table 11: Cement manufacturing plants - locations and production capacities in Saudi Arabia

Serial	Company	Location	Cement Production Capacity	Products	Info
1	Saudi Cement	Near Al-Ehssa , Eastern Province	9.7 Mio tons/Year (= daily 28,000 tons of Clinker)	- Sulfate Resistant Cement - Ordinary Portland Cement	3 kiln lines.
2	Tabuk Cement	Duba, Northern Province	3.3 Mio tons/Year (= 3 Mio tons/Year of Clinker	- Ordinary Portland Cement - Portland Pozzolan Cement - Sulfate Resisting Cement	2 kiln lines. 3 grinding lines.
3	Yanbu Cement	Near Yanbu, Red Sea	10 Mio tons/Year (= 7.0 Mio tons/Year of clinker)	- Ordinary Portland Cement - Portland Pozzolan Cement - Sulfate Resisting Cement	5 kiln lines.
4	Al-Jouf Cement	Al-Jouf	1.8 Mio tons/Year	- Sulfate Resistant Cement - Ordinary Portland Cement	–
5	Southern Province Cement	Jazan	1.8 Mio tons/year	Ordinary Portland Cement	2 kiln lines
6	Southern Province Cement	Tuhamah	4.5 Mio tons/year	Ordinary Portland Cement	3 kiln lines
7	Southern Province Cement	Beeshah	2.7 Mio tons/year	Ordinary Portland Cement	2 kiln lines
8	Al-Safwa Cement	Jeddah	2.2 Mio tons/year	- Ordinary Portland Cement - Portland Pozzolan Cement	
9	City Cement	Al-Riyadh	1.75 Mio tons/year	- Sulfate Resistant Cement - Ordinary Portland Cement	

Source: (CEMNET 2022); Cement manufacturing company's websites

Note : The average global clinker-to-cement ratio is 0.721 (according to https://www.iea.org/reports/cement)

Green hydrogen can help decarbonize cement production by replacing some or all of the fossil fuels used to heat kilns and calcine limestone. Cement production is responsible for about 6.5% of global CO_2 emissions, mainly from fuel combustion and the heat reaction of limestone. Challenges and limitations include the compatibility and safety of existing kiln systems with high concentrations of hydrogen, and the inability to address CO_2 emissions from the calcination process, which account for approximately 60% of cement production emissions.

The following graph shows the annual production of cement in the Kingdom over the last decade.

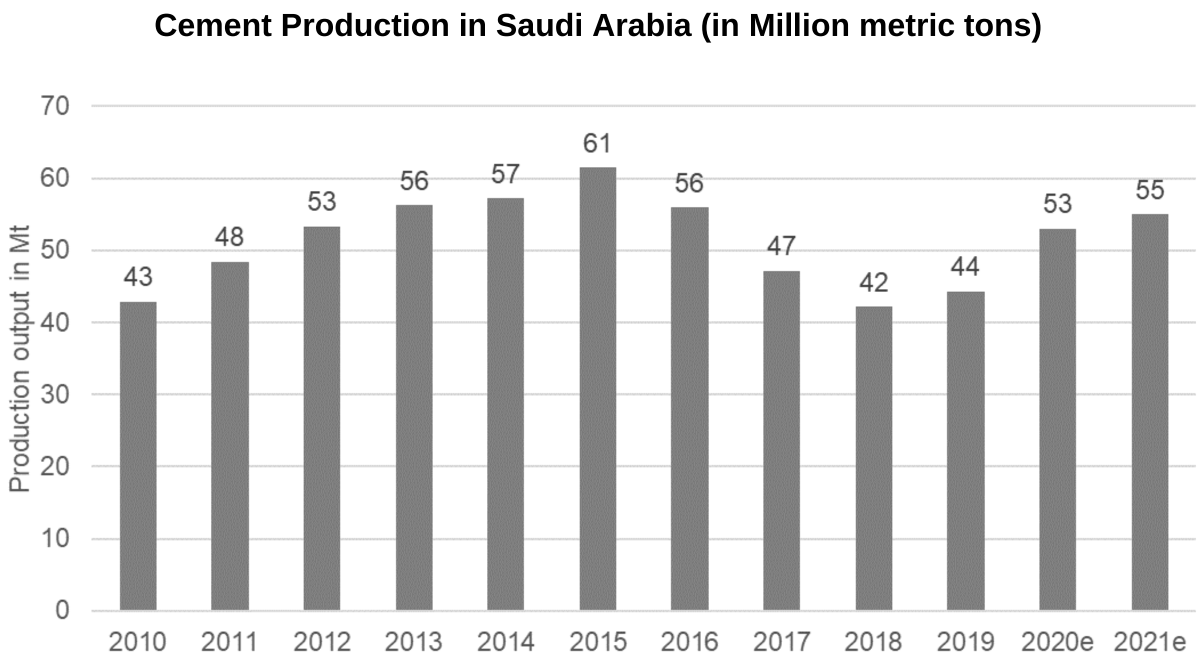


Figure 60: Development of cement production in Saudi Arabia
Source: KAPSARC; https://datasource.kapsarc.org/explore/dataset/saudi-cement-production-data/export/?disjunctive.cement&sort=year, May 2023
Data for 2020 and 2021: Statista Research Department, Jan 2023

From the following Table 12, it is anticipated that green hydrogen demand for the global cement industry would reach an amount of about 312 million tons per year.

Table 12: Cement manufacturing heating energy demand in Saudi Arabia

Heat Energy Input Options	Required Heat / 1 cement ton	Heating Fuel Amount (kg/cement ton)	Tons of fuel for **Global** cement annual product of 4 billion tons	Tons of fuel for **Saudi Arabia** cement annual product of 55 million tons
Coal	4.7 mio Btu = 1.184 mio kcal	181.2	725 million	---
Natural Gas		155.76	623 million	8.6 million
Hydrogen		78	312 million	4.3 million

Source: (M. Fadayini et al. 2021, p 6)

However, for the Saudi Arabian cement industry, the demand for low-carbon hydrogen (or its derivatives) could reach 4.3 million tons/year.

For Saudi Arabia, the following Table 13 shows the hydrogen demand for the different major applications: refineries, ammonia and methanol plants, steel DRI and cement production. For comparison, the world figures are shown in the two columns on the right. For both Saudi Arabia and the world, the amount of product produced (refined crude oil, ammonia produced, etc.) and the corresponding hydrogen demand are shown. Although conventional DRI steel and cement production do not use hydrogen, these processes contribute significantly to greenhouse gas emissions - both steel (WEForum 2021b) and cement (MIT 2021) contribute about 7% of global GHG emissions each. To make them greener, they can be adapted to use carbon-neutral hydrogen, although hydrogen is not a traditional requirement.

Table 13: Hydrogen demand or replacement potential in Saudi Arabia for existing industrial value chains

Million tons per year	KSA			Global	
Application area	**Production [Mt]**	**Year**	**Hydrogen demand [Mt]**	**Production [Mt]**	**Hydrogen demand [Mt]**
Oil refinery* [Mt]	152.2	2021	1.5	3945.2	39.8
Ammonia production [Mt]	4.5	2019	0.9	178.9	33.8
Methanol production [Mt]	4.9	2018	0.8	98.0	14.6
DRI Steel production [Mt]	7.5	2019	0.4	119.2	6.0
Cement production [Mt]	55.0	2021	1.4	4270.0	111.0
			5.0		**205.2**

*Million tons (Mt) of Oil Equivalent as Refineries Input (Crude Oil)

Sources Saudi Arabia Production:

https://www.stats.gov.sa/sites/default/files/Oil_and_Gas_Statistics_2021_EN.xlsx; Table 2.1

https://www.nationmaster.com/nmx/timeseries/saudi-arabia-ammonia-production#dataviz

http://www.mgc-a.com/methanol/locations/index.html

https://take-profit.org/en/statistics/steel-production/saudi-arabia/

Sources Global Production:

(IEA 2021d); Hydrogen Demand: (IEA 2022b)

https://www.ifastat.org/supply/Nitrogen%20Products/Ammonia

(IRENA and Methanol Institute 2021, p 22)

https://gmk.center/en/news/global-dri-production-increased-by-14-in-2021/

https://www.azocleantech.com/article.aspx?ArticleID=1606 (specific consumption: 50 kg of hydrogen are needed to produce 1 ton of steel)

https://www.iea.org/reports/cement

Note: Saudi Arabia hydrogen demand is calculated using the global average specific consumption. This can only be an approximation, since local conditions and technological infrastructure on site are not taken into account in this calculation procedure. Due to a lack of data, this calculation method had to be used in the knowledge that the calculated values can only serve as a rough guide.

4.3.3 Economic potential for hydrogen production

Cost of green hydrogen (electrolysis)

The Saudi government signed power purchase agreements (PPAs) for seven solar power projects in January 2021 at an average price of approximately $18.3/MWh (PV-Magazine 2021; PVTECH 2020; Renewables Now 2021, Saudi Gulf Projects 2021). This average price is not significantly different from the PPA price of $19.9/MWh awarded to the 400 MW Dumat Al-Jandal Wind Farm project in 2019. Using $18.3/MWh as a benchmark for renewable energy in the Kingdom, the cost of producing green hydrogen is $2.16/kg (Figure 62).

Both new world record solar tariffs were awarded in Saudi Arabian tenders in April 2022 - the first for the 600 MW Al Shuaiba PV IP project with a new world record of $ct1.04/kWh, and the second at $ct1.24/kWh for the 1.5 GW Sudair solar complex.

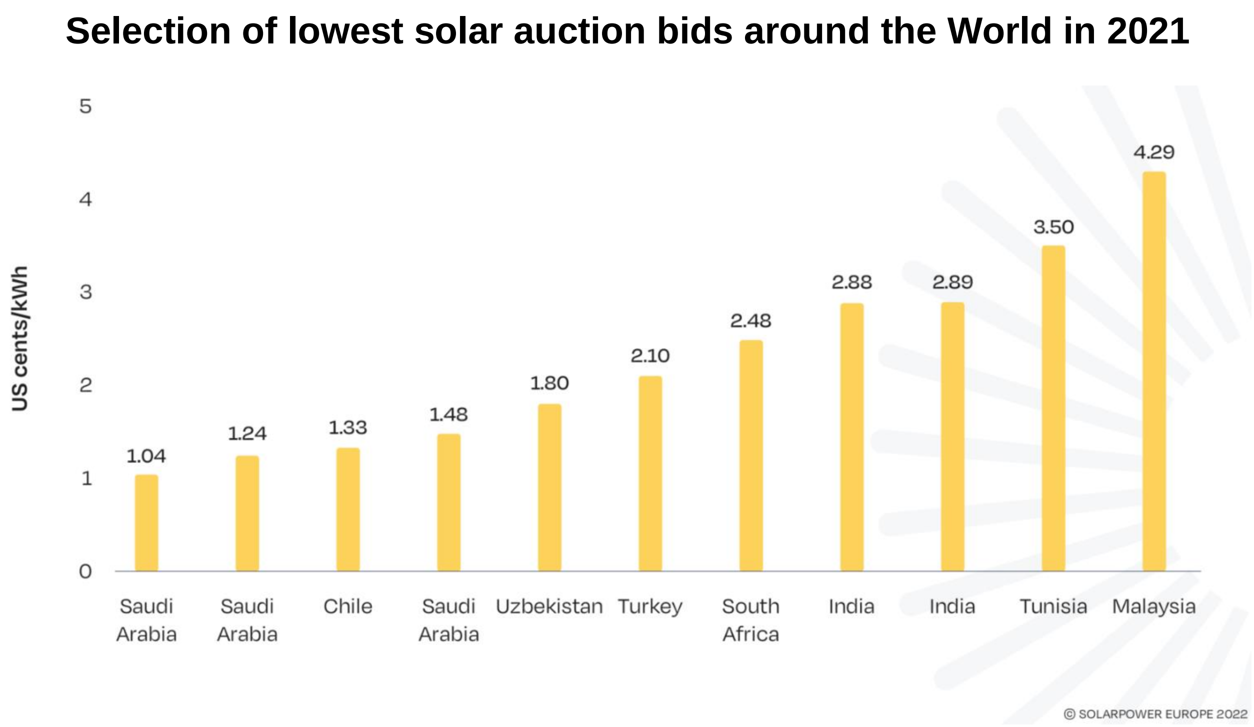


Figure 61: Selection of lowest solar auction bids around the world in 2021

Source: (SPE 2022, p 11)

Current hydrogen production costs in Saudi Arabia

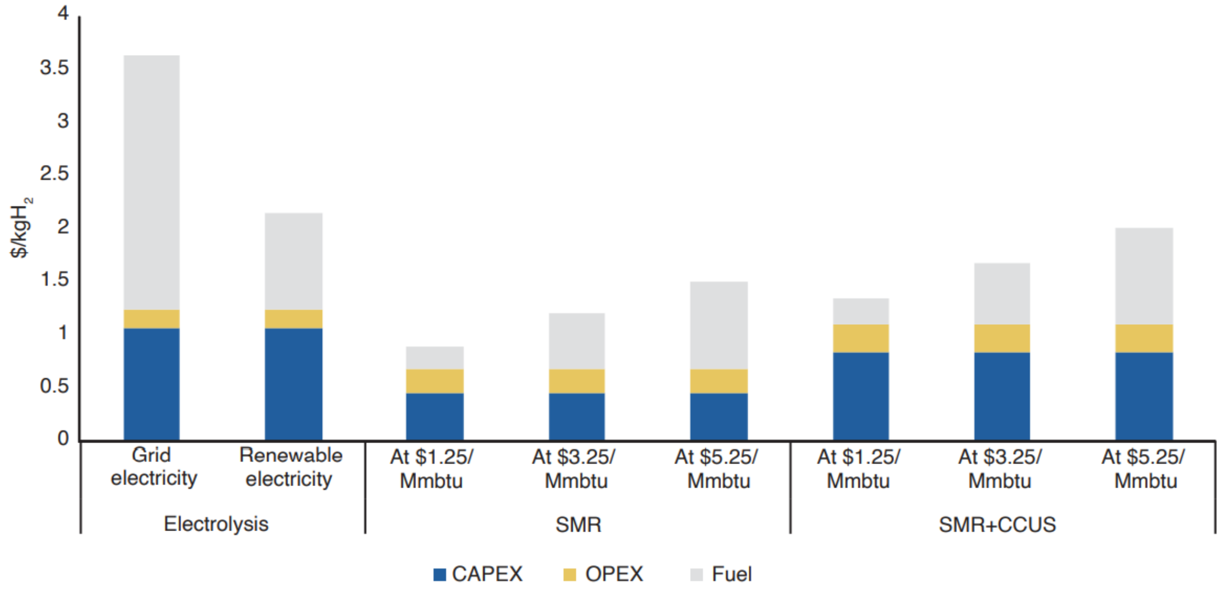


Figure 62: Current hydrogen production prices as per generation process

Source: (KAPSARC 2021, p 14)

The costs in Figure 62 are based on an average capacity utilization of 60%, which is higher than standalone solar or wind production. A combination of solar and wind power can achieve the desired electrolyser utilization, while using solar power alone for green hydrogen production is not ideal because it excludes balancing, transmission, substation, and storage costs. It also ignores continuously generating renewables that meet the hydrogen production utilization assumptions.

Current and projected hydrogen production costs in Saudi Arabia

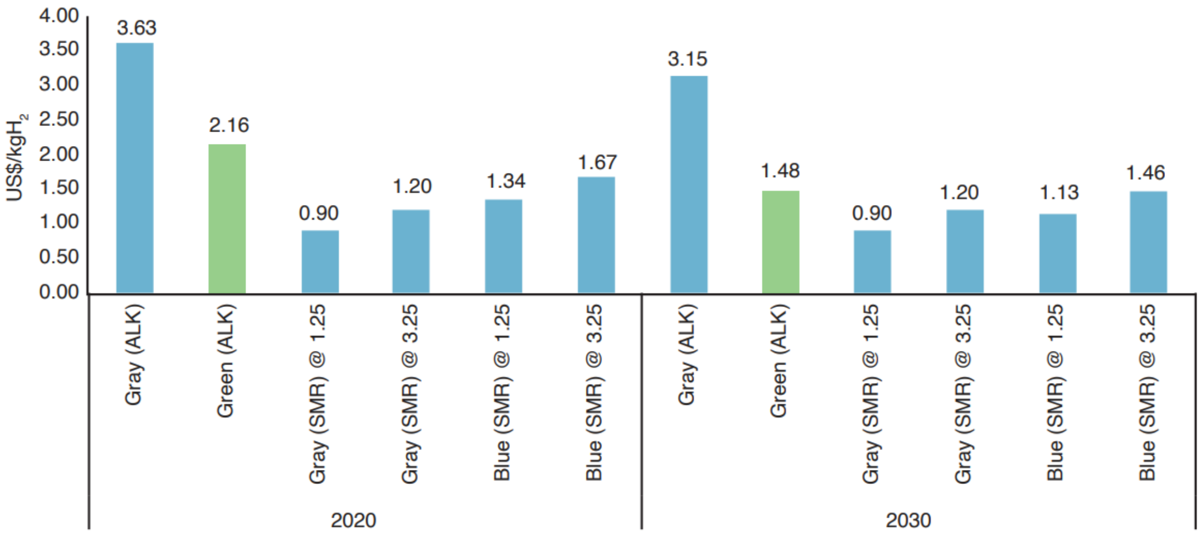


Figure 63: Current hydrogen production prices as per the type/color of the hydrogen

Source: (KAPSARC 2021, p 15)

At $2.16/kg today, green hydrogen is more expensive than grey or blue hydrogen, but cheaper than hydrogen produced by alkaline electrolysis using electricity from the grid with the current electricity generation mix. However, as electrolysis technology and renewable electricity costs decrease, green hydrogen production costs are expected to decrease the most over the coming decades.

Proposed tariffs for new solar projects suggest that green hydrogen could become more affordable in Saudi Arabia. If the cost of renewables falls to $13/MWh by 2030, the cost of producing green hydrogen could fall to around $1.48/kg, as shown in Figure 63. Lower capital investment and lower renewable energy costs will be the main cost drivers. If electrolyser costs fall to $400/kW, renewable energy costs could be below $10/MWh by 2030, **potentially leading to green hydrogen prices as low as $1/kg by 2050**, as shown in Figure 64. These cost reductions, coupled with increased efficiency, could lead to a 31% reduction in hydrogen costs by 2030 and a 53% reduction in the long term.

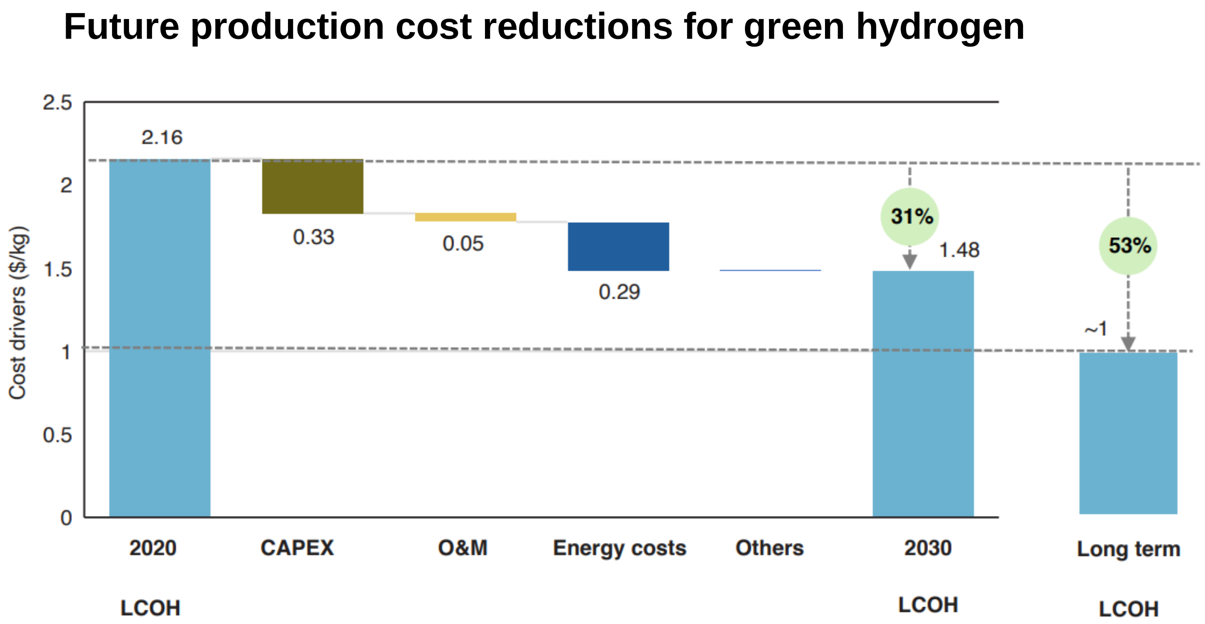


Figure 64: Future reduction in hydrogen production cost

Source: (KAPSARC 2021, p 18)

The estimated delivery cost of hydrogen from Saudi Arabia to the global markets

Saudi Arabia's low-cost hydrogen production base presents significant opportunities as the global carbon footprint declines. Its resources can be monetized through exports or domestically in carbon-intensive industries. Assuming a green hydrogen production cost of $1.48/kg by 2030, the delivered hydrogen cost (including carrier conversion, shipping, and dehydrogenation) from the western region of Saudi Arabia to the port of Rotterdam via the Suez Canal would be between $3.50/kg and $4.50/kg, as shown in Figure 65, depending on the hydrogen carrier used (KAPSARC 2021).

Estimated delivery cost of hydrogen derivatives from Saudi Arabia to the global markets

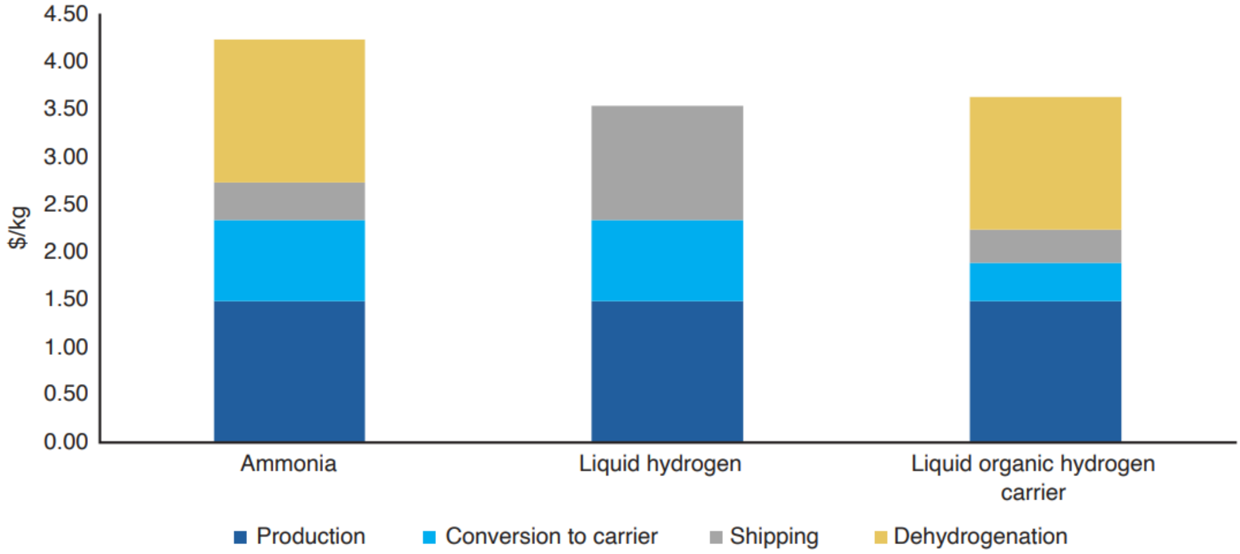


Figure 65: Estimated delivery cost of Hydrogen derivatives from Saudi Arabia to the global markets

Source: (KAPSARC 2021, p 25)

More than 300 GW of electrolyser capacity at 8,000 full load hours is required to produce 50 Mt of hydrogen per year. About 2,200 TWh of green electricity is needed to produce this amount (50 Mt) of green hydrogen per year (World Bank Group 2022).

Compared with global demand and based on current trends, total refinery hydrogen demand is expected to grow by 7% to 41 MtH2/yr in 2030 (IEA 2019, p 95).

5 Saudi Arabia's potential as a world energy provider

In chapter 4, the current state of renewable energy and water desalination projects in the Kingdom of Saudi Arabia (Saudi Arabia) was examined, along with hydrogen (H_2) production, its derivatives, and their consumption across various applications.

In chapter 5, the fuel trade routes involving key off-takers, the effects of transportation costs on H_2 exports, and the connection between hydrogen demand and energy markets in Saudi Arabia and other countries will be explored. Furthermore, hydrogen projects and agreements between Saudi Arabia and major European and Asian countries are discussed.

5.1 Introduction

In 2021, Saudi Arabia's total exports value was $286.5 billion, with petroleum exports (Mio. $ 202,166) accounting for a significant 70.6% of this (OPEC 2022). However, the share of petroleum in exports is predicted to decrease in the medium to long term. The potential for hydrogen exports to compensate for declining oil revenues is an essential part of this study. However, it is not easy to determine today the future price for zero-emission hydrogen and derivates and its profit margin.

Saudi Arabia's Circular Carbon Economy (CCE) approach aims to reduce CO_2 emissions by 278 million metric tons per year by 2030. The country plans to derive 50% of its power from renewables by 2030 and achieve carbon neutrality by 2060. Currently, 14 renewable energy projects with a total capacity of about 10 GW are in development (see Table 8), set to reduce around 20 million tons of CO_2 emissions per year once operational (ZAWYA 2022).

Saudi Arabia aims to become a leading producer and exporter of clean hydrogen, with the world's largest green hydrogen plant set to start producing up to 600 tons per day in 2026. Aramco, Sabic, and Ma'aden have received the world's first independent certifications for blue hydrogen and ammonia production, enhancing Saudi Arabia's export infrastructure for clean fuels (ZAWYA 2022).

Saudi Arabia launched a greenhouse gas (GHG) crediting and offsetting scheme in early 2023 to encourage efforts and investment projects to reduce GHG emissions across all sectors in the Kingdom (ZAWYA 2022).

In addition, from an economic perspective, Saudi Arabia can greatly benefit from the transition to fossil-free energy by conserving its vast oil and gas reserves, which will last for approximately 70 to 80 years at current production rates and known reserves until they are finally depleted. Rather than burning oil and gas derivatives (refined products) directly to generate energy (electricity and heat), it is more economically viable to minimize the use of these products as fuels and instead use them in petrochemical industrial processes.

These petrochemical products have numerous applications and their global demand continues to increase. This forward-looking strategy involves preserving current oil and gas reserves for optimal utilization by future generations in Saudi Arabia. **Instead of burning hydrocarbons and release CO_2, better transform them into materials like plastic, where carbon is bound for a longer period and which aligns with the rising global demand for petrochemical-based products.**

5.2 Overview of the trade routes of fuel, and energy from Saudi Arabia to key off-takers

Pipelines are an ideal infrastructure means for large-scale transport of energy carriers. For longer distances (several thousand kilometers), shipping by vessels might be the least cost option as shown in Chapter 3.6.1 and is depicted for hydrogen in Figure 68.

Often, existing infrastructure can be utilized, for example pipelines for natural gas can be modified to also be used for hydrogen transport. The locations of the oil and gas fields and infrastructure like pipelines, oil processing complexes, refineries, and major exporting terminals/ports can be taken from Figure 66.

Saudi Arabia major Oil and Natural Gas Infrastructure

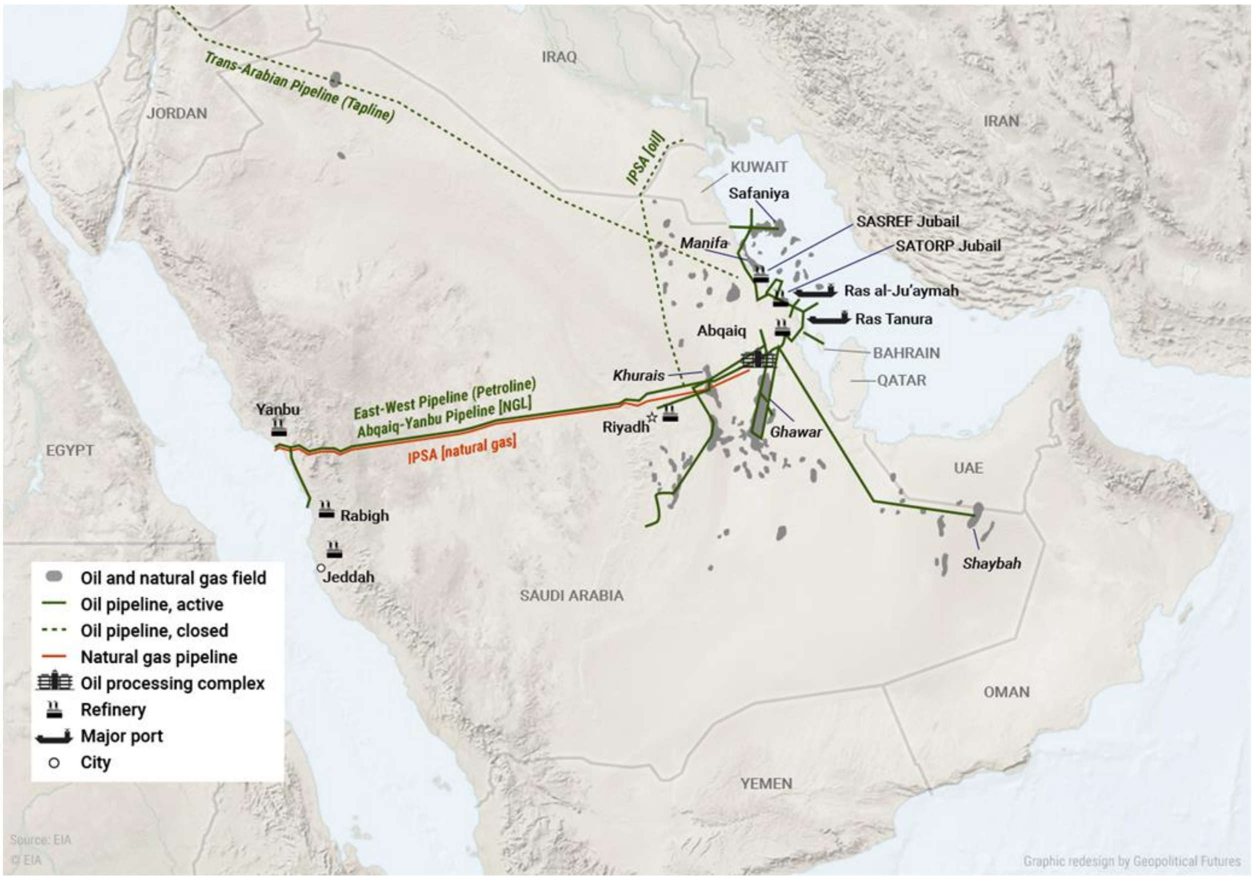


Figure 66: Saudi Arabia's major oil and gas infrastructure

Source: (GPF 2016)

The wider picture for the whole Middle East is provided in Figure 67. Taking into account the infrastructure of neighboring countries some oil and gas pipelines are established in Egypt, Turkey and the border of Turkmenistan. Oil and gas pipelines are connected with the port of Yanbu on the Red Sea where large refineries are present.

Oil and Gas Pipeline Infrastructure in the Middle East

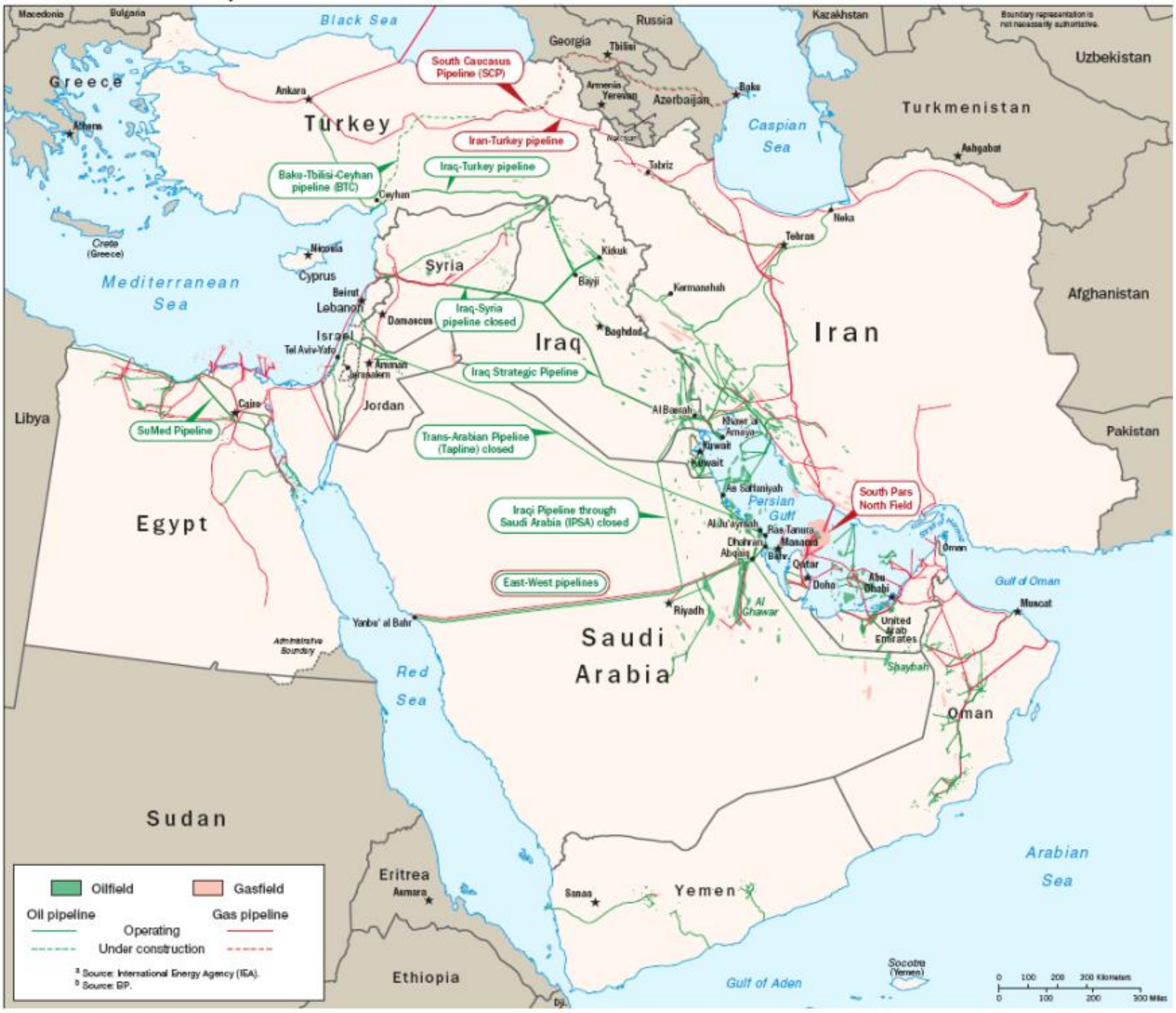


Figure 67: Oil and Gas Pipeline Infrastructure in the Middle East

Source: (EIA 2017)

5.3 Transportation Costs and Form of Hydrogen Delivery

The transportation costs of hydrogen and derivatives are determined by the two main factors:

i. Product to be transported (hydrogen or ammonia for example), and

ii. Form of transportation; either hydrogen gas carrier pipeline or maritime carrier shipping (liquefied hydrogen or LOHC such as ammonia and methanol).

So, it is essential to identify the specific form of hydrogen or its derivatives, as this can significantly impact various aspects of the transportation process, including production methods, liquefaction or gasification facilities, shipping terminals, maritime carriers or ships, and more.

As for the optional transportation method of energy utilizing the power grid, this option is not going to be considered in the near future, since there are no plans for strong high-voltage grid connections between the European Union and Saudi Arabia. However, a limited capacity grid connection is planned between Saudi Arabia and Egypt (Note: The electricity interconnection project will allow Saudi Arabia and Egypt to exchange up to 3,000 MW of power), as well as a grid connection between Egypt and the EU (via an undersea cable that will carry 3,000 MW electricity and connect northern Egypt directly to Attica in Greece), which could be utilized for electric energy transfer between Saudi Arabia and the European Union, but with limited capacity.

However, for transportation between Saudi Arabia and Japan, Korea and China, it is obvious that the power grid connection is not feasible due to longer distances.

The form of hydrogen/derivatives can affect the transportation process dramatically:

i. How is the largest Asian consumer receiving hydrogen?

ii. How is the largest European consumer receiving hydrogen?

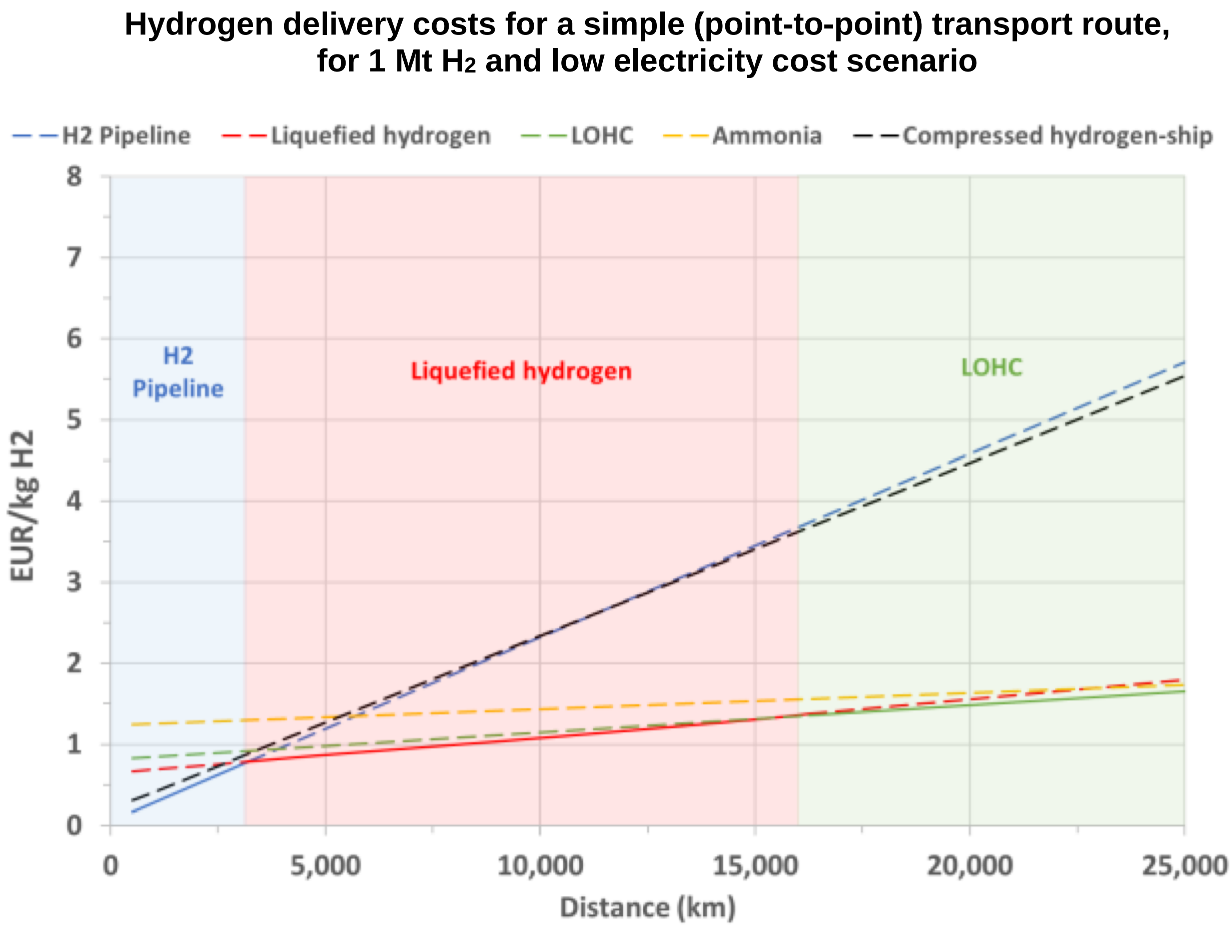


Figure 68: Influence of transport distance between a single production and delivery point on the hydrogen delivery price

Source: (European Commission 2021, p 3)

As provided in Figure 68, for a distance of up to ~2,600 km, H_2 pipeline and compressed H_2 shipping are the cheapest options. Some other sources assume this would be the least cost option up to 5,000–8,000 km if existing pipelines can be converted. However, other sources, like shown in Figure 40 provide shorter distances of less than 2,000 km for ammonia shipping to be more cost-effective. Longer distances of 2,600-16,000 km should be covered with liquefied hydrogen, ammonia or other power to liquids such as methanol (European Commission 2021, p 3).

5.4 Overview on the hydrogen consumption rate in the global energy market and the energy market ties between Saudi Arabia and other countries

Figure 69 shows that the main global hubs for the oil market are in Saudi Arabia, China and USA. The small circles show exporting countries and the arrowheads where the oil is delivered.

Major Oil Trade Movements 2021
Trade flows worldwide (million tons)

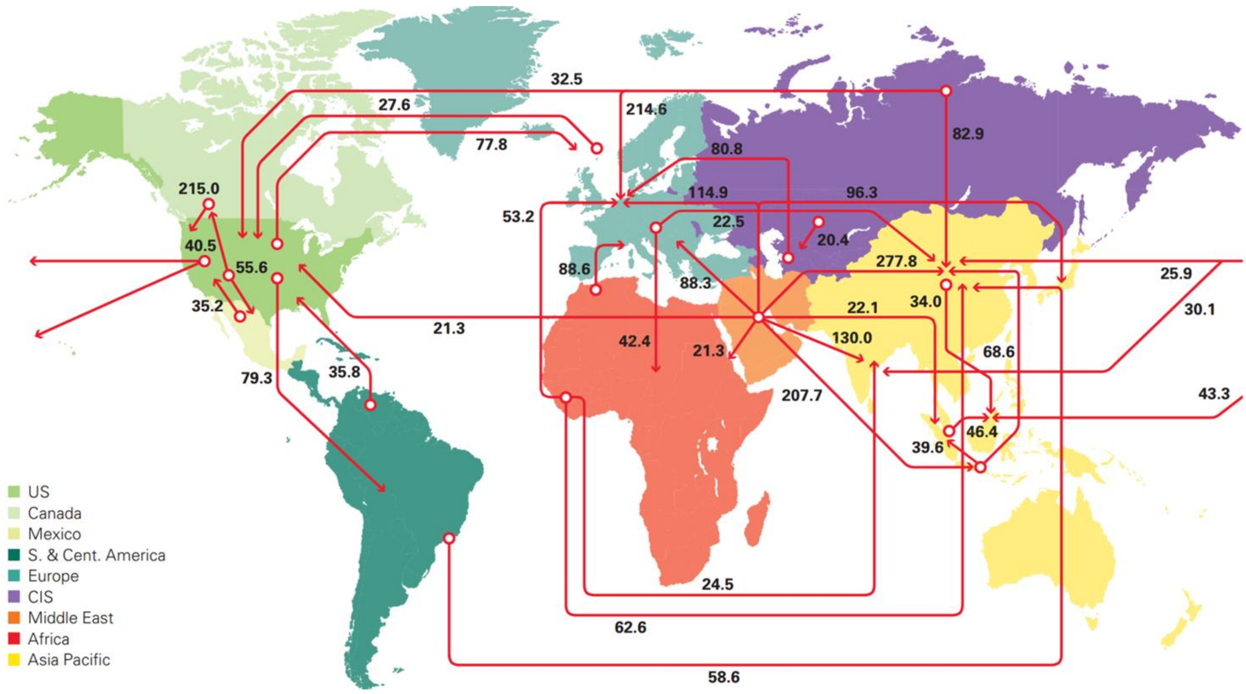


Figure 69: Major oil trade movements 2021

Source: (BP 2022, p 28)

An early momentum can be recognized as traditional energy importers like Japan and South Korea, willing to pay premium prices, are increasingly pursuing the possibility of importing hydrogen through ocean shipping (e.g., with Australia, see HESC-Project below) either through LH_2, LOHCs, or NH_3.

European countries are also welcoming the prospects for both intra-regional and international hydrogen trade. Traditional energy exporting regions like Australia and the Middle East are increasingly positioning themselves for hydrogen exports.

The Japan-Australia Hydrogen Energy Supply Chain (HESC) project

Japan and Australia are currently working on a Hydrogen Energy Supply Chain (HESC) project, the world's first endeavor to ship hydrogen across the ocean. It aims to safely produce and transport clean liquid hydrogen from Australia's Latrobe valley in Victoria to Kobe in Japan. HESC hopes to demonstrate the viability of an end-to-end hydrogen supply chain.

In 2020, Saudi Arabia **exported** for $2.09B of ammonia, making it one of the largest exporters of ammonia in the world. In the same year, ammonia was the 8th most exported product in Saudi Arabia.

The main destination of ammonia exports from Saudi Arabia are: **India ($945M)**, Brazil ($237M), **South Korea ($210M)**, Bangladesh ($136M), and the United States ($127M).

5.5 Planned Hydrogen Projects in Saudi Arabia

VISION 2030

Saudi Arabia aims to ensure economic security by becoming the top global supplier of hydrogen, as it aligns with the goals of Vision 2030. Leveraging the country's expertise in hydrogen, chemicals production and carbon capture and storage, Saudi Arabia focuses on blue and green hydrogen production. The development of a clean hydrogen industry supports Saudi Arabia's pursuit of a circular carbon economy and may help facilitate the global energy transition. Although an official hydrogen strategy is still under development, the country is actively working on multiple hydrogen projects, including the Neom green hydrogen project and collaborations with international partners such as South Korea (CSIS 2022b). As part of Saudi Arabia's Vision 2030, renewable energy is targeted to account for 50% of the electricity mix.

NEOM

The Neom green hydrogen project in northwest Saudi Arabia has secured $8.5 billion in funding from two government funds and a consortium of 21 financial institutions, making it the first gigawatt-scale renewable hydrogen project to obtain the necessary financing for construction. The project, which will use 4.6 GW of wind and solar power capacity to supply 2.2 GW of electrolysers, aims to produce about 600 tons of green hydrogen daily. This hydrogen will be converted into liquid ammonia on-site and exported globally by Air Products, which owns a 33.3% stake in the project developer, Neom Green Hydrogen Company (Hydrogeninsight 2023b).

Saudi Arabia Renewable Energy Hub (SAREH)

InterContinental Energy, Saudi Aramco, and Modern Industrial Investment Holding Group have announced in 2021 to collaborate in the so-called Saudi Arabia Renewable Energy Hub (SAREH). This project is part of Saudi Arabia's decarbonization push, aiming for hydrogen production of 2.9 million tons per year by 2030 and 4 million tons per year by 2035. Aramco's ultimate goal is to achieve net zero for Scope 1 & 2 emissions across its wholly-owned operated assets by 2050 (AMMONIA ENERGY ASSOCIATION 2021).

Initiatives

Saudi Arabia's energy and climate change efforts and endeavors are embedded in regional and international initiatives, the most prominent of which are the Saudi Green Initiative (SGI) and the Middle East Green Initiative (MGI) (Saudigazette 2023).

Cooperation with Egypt

Egypt is an important link for Saudi Arabia to transport the anticipated product of green hydrogen and other PtX fuels to Europe. On 21 June 2022, Egypt and Saudi Arabia signed 14 investment deals worth $7.7 billion in total. The agreements relate to the development of renewable energy, including green hydrogen, as well as infrastructure and e-commerce.

Future vision of hydrogen backbone in Saudi Arabia

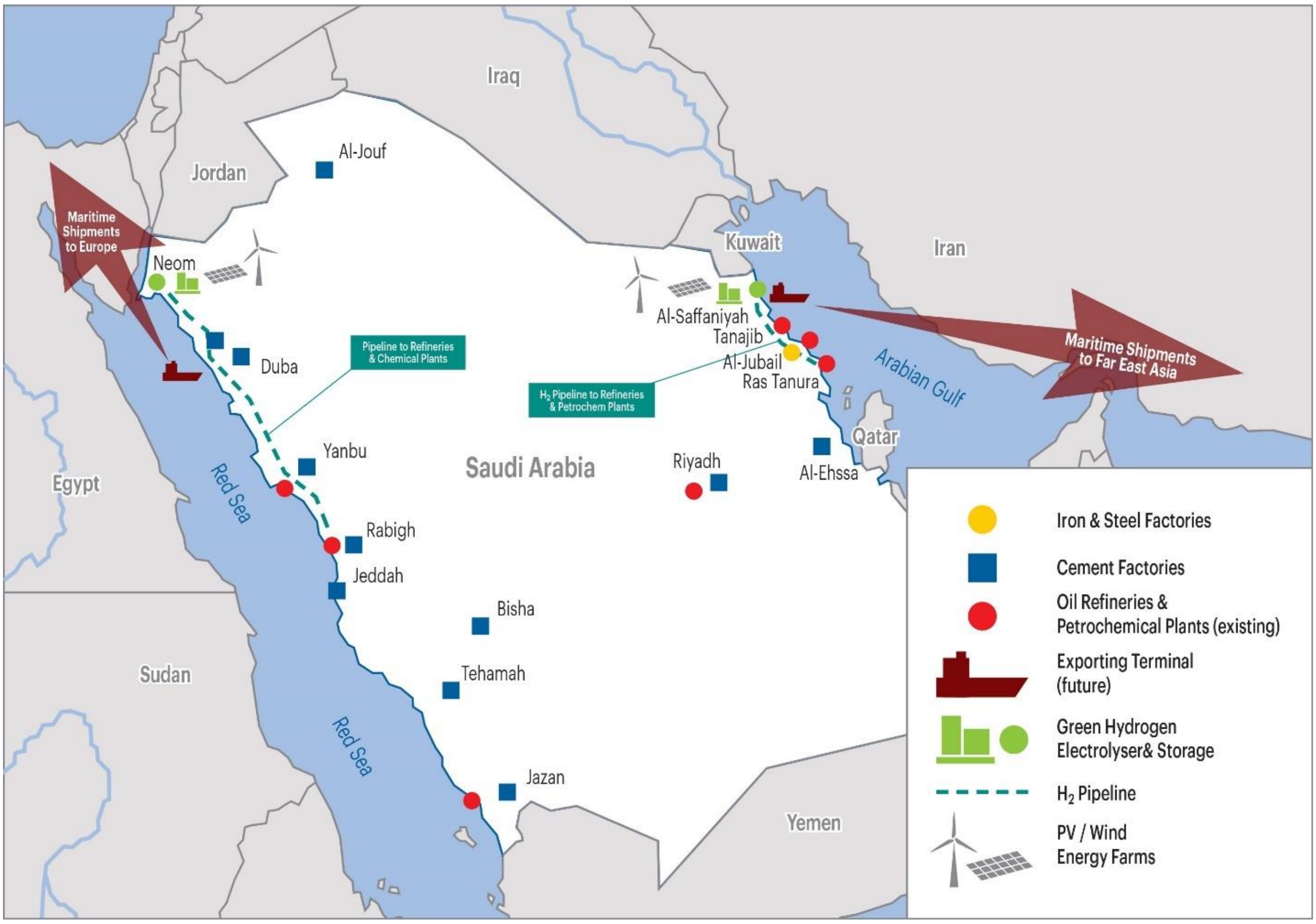


Figure 70: Future vision of hydrogen backbone in Saudi Arabia

Source: ECG

Figure 70 is showing the major industrial activities in Saudi Arabia, including:

- Major refineries, chemical and petrochemical plants. (existing)
- Iron & Steel manufacturing plant (Hadeed at Jubail). (existing)
- Major cement factories. (existing)
- Tentative locations of green hydrogen electrolyser plants. (proposed)

- Renewable energy major farms to feed water RO and electrolyser plants. (proposed)
- Main maritime exporting terminals of green hydrogen and derivatives (proposed), noting that:
    - 14’000 km is the trip distance between Al-Jubail and Kobe port in Japan.
    - 8’000 km is the trip distance between Dhuba port and Rotterdam.
- Pipelines to transport green hydrogen or derivatives to cement factories, refineries, Hadeed plant, and chemical/petrochemical plants. (proposed)

6 Conclusion

The results in a nutshell:

- China and India, experiencing significant growth in primary energy consumption due to ongoing population increases, especially in the latter, face significant challenges in their energy transitions. Both nations need substantial investments in renewable energies and related infrastructure like electrical grids, electrolysers, and storage systems. While China has progressed in renewable energy production, its high demand for primary energy makes the transition more challenging. For the foreseeable future, these two populous countries will rely heavily on energy imports. Their respective goals to achieve climate neutrality, 2060 in China and 2070 in India, are notably later than the common target of 2050 announced in many countries.
- Europe and Japan are predicted to continue to decrease their primary energy consumption due to declining populations and enhanced energy efficiency through electrification, and fossil fuels being replaced by carbon-free hydrogen and its derivatives. These countries aim to minimize energy imports for financial reasons, but high industrialization and limited land for renewable energy imply that imports will be needed. European countries are thus interested in importing about half of their primary energy needs as preferred green hydrogen or derivatives, with initial projects initiated by companies aiming to meet their net-zero emissions targets. . Japan and South Korea have already initiated import projects - mainly in the fields of blue hydrogen and ammonia.
- As of today, Spain appears as a suitable candidate able to supply green hydrogen or PtX to the European market, next to Morocco, Algeria and Tunisia thanks to the geographic proximity to European demand centers. Saudi Arabia unfolds strong credentials to become a supplier of these carbon-neutral fuels to Europe, which was not the case in the past when Saudi Arabia delivered oil and oil products as well as ammonia and methanol mainly to the Asian markets.
- Green hydrogen costs are primarily driven by the cost of electrolysers, electricity prices, and the need for reasonable full load hours for economic feasibility. Costs for storage, transportation, and hydrogen conversion in PtX also play a role.
- As soon as sufficient renewable energy capacities are installed, surplus electricity can be used for hydrogen production. In pilot projects or with economical production and use, hydrogen can be produced in parallel from renewables even with a low share of RE in electricity generation. Hydrogen has the capacity to store larger quantities of energy and can contribute to grid stability. For the Gulf states and Saudi Arabia in particular, there are enormous opportunities for domestic value creation: from local production of renewable energy systems and components to advanced commodities like green ammonia and methanol; the latter for domestic and export purposes.
- Saudi Arabia should consider opportunity costs when using oil or gas for electricity generation, as these resources could be exported for additional revenues. A "fuel saver" approach can be initially adopted: using renewable energy when available and resorting to fossil fuels otherwise. This method mainly requires investment in renewable energy capacities but can significantly reduce fossil fuel consumption, extending the availability of these resources for usages other than combustion.
- A controlled and regulated expansion, guided by a comprehensive hydrogen roadmap, is recommended for Saudi Arabia to ensure a consistent supply of hydrogen, for domestic usage and exports, and its affordability. This strategic approach will demonstrate Saudi Arabia's commitment, attract investments, and support the monetization of resources during the energy transition. To push hydrogen beyond the market adoption tipping point, various regulatory and market interventions are needed.

6.1 Findings

Climate neutrality and the reduction of CO_2 levels in the atmosphere are high on the agenda of all countries that have signed the Paris Agreement. The investigated countries in Europe and Japan and South Korea explicitly announced that they will need to import a significant amount of hydrogen that is carbon neutral. The mentioned countries recognize that the consequences of climate change are already clearly visible today and cost society billions of US dollars yearly. If humanity fails at mitigating or stopping these catastrophic developments, it will damage and destroy its livelihood and that of many living creatures and plants. This requires a united and globally coordinated action.

However, an energy system cannot be changed that quickly. The energy transition will take place in several phases, whereby these are not sharply separated from each other and rather merge into one another. In the first phase, grid parity is reached, which means that power from renewable energy has lower, or equal costs compared to the electricity tariff.

This is already the case in almost all countries with installed solar and wind power systems.

In the second phase, the electricity demand is covered almost fully by renewable sources. Typically, 20 to 30% of the electricity share in the grid will not destabilize it. However, if the share is getting significantly higher, some measures must be taken to compensate for renewable energy sources´ volatility. Such a power grid can be kept stable via load management, power plants that can be quickly switched on (and off), such as electricity-controlled combined heat and power plants. This is known as a smart grid, in which pumped hydropower stations, batteries or other electricity storage technologies can also be used. Even at this stage, fuel cells could play an important role in stabilizing the power grid.

Additional renewable capacities can be deployed to generate hydrogen which will replace energy carriers that release CO_2 when utilized. This is the third phase and hydrogen or its derivates can then bring sector coupling to the next level: it replaces conventional fuels for transport or the hydrogen is used in industries instead of petrochemical products.

It is also possible to continue producing hydrogen by using natural gas in a steam methane reformation (SMR) process and store the CO_2, a byproduct, in the ground (CCS) or utilize (monetize) it for example to produce methanol (CCU).

6.1.1 Implications of the energy transition

To achieve climate neutrality, the energy industry must be restructured or expanded. For example, Figure 71 shows the final energy demand for Germany with the uncertainties that still exist. Key trends are 1) electrification which will also bring a higher overall system efficiency: think of heat pumps that have a coefficient of performance (COP)[5] of typically 3 to 4. Other examples are electric drives which are typically more efficient than fuel-powered engines. Trend 2) is characterized by increased production of hydrogen and derivates that will be used in industry, aviation and shipping, thus in all those processes where battery storage would not be feasible or cannot be driven by electrical energy.

[5] Coefficient of Performance (COP): The COP is a ratio between the rate at which the heat pump transfers thermal energy (in $kWh_{thermal}$), and the amount of electrical power required to do the pumping (in $kWh_{electrical}$). For example, if a heat pump used 1kWh of electrical energy to transfer 3 kWh of heat, the COP would be 3; adapted from GOV.CA (2022).

Final energy mix in the scenarios of the Ariadne project for the overall energy system in Germany

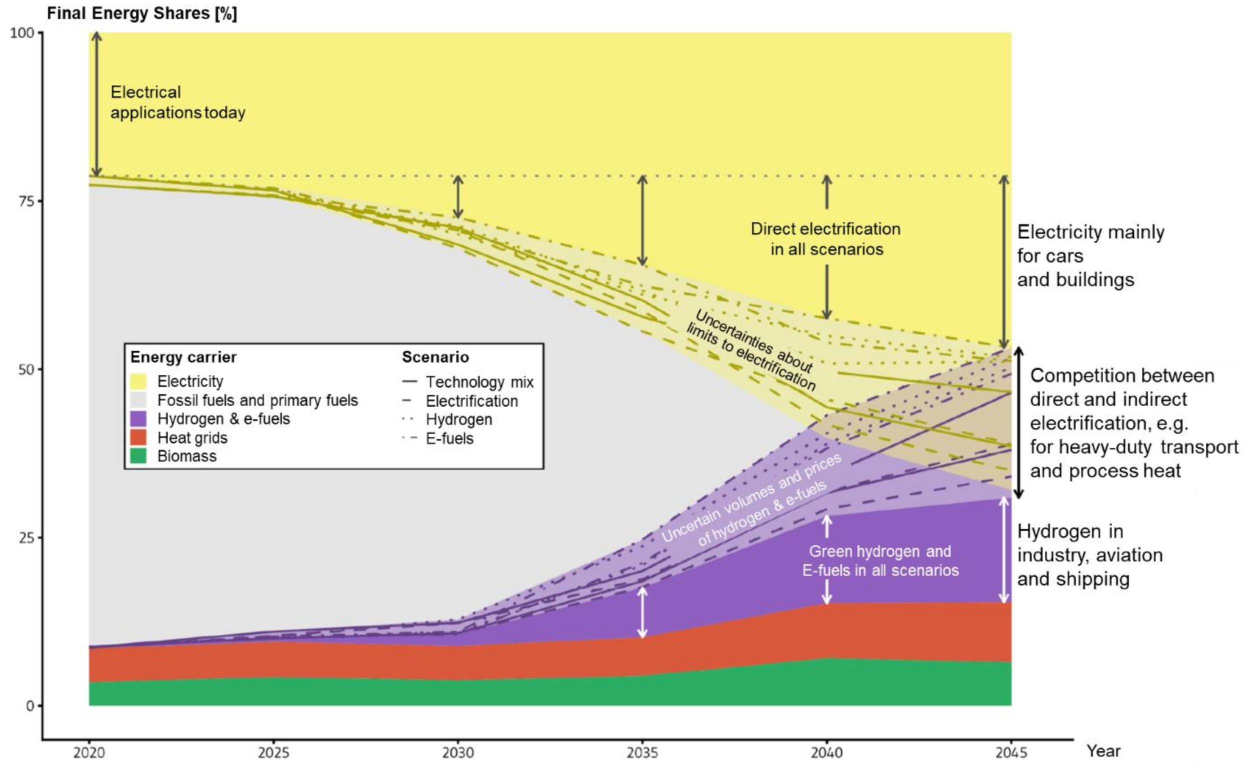


Figure 71: Final energy mix in the scenarios of the Ariadne project for the overall energy system in Germany.

Source: (Ariadneprojekt 2021, p 17) Graph text translated by authors

With a high share of solar and wind in the power grid, there will be periods when there is significant excess of electrical energy – this can amount to 10 times the current power consumption. This energy can be stored or converted into hydrogen via electrolysis. Also, there will be periods when there is almost no power generated by sun and wind power, for example at the so-called dark lull. The power generation system must be flexible and needs to have reserve capacities like combined heat and power stations, or fuel cells and must be controllable for example with switchable loads.

6.1.2 Off-taker markets

Hydrogen can be used as a base material for producing all other electricity-based synthetic fuels such as synthetic methane, methanol, liquid hydrocarbons and ammonia.

There are already several off-takers for hydrogen in the petrochemical and chemical industries, and hydrogen can easily replace carbon for steelmaking (DRI). Hydrogen is consumed in the production of ammonia and methanol, and fuel cells can convert hydrogen (back) into electricity.

What does it cost to avoid CO_2-emissions? And which sectors should be addressed first? Figure 72 shows the global marginal abatement cost curve for CO_2 for utilizing hydrogen priced at $1/kg by 2050. The sectors on the left side of the graph have the lowest CO_2 abatement costs and should be targeted first. In numbers, global energy-related CO_2 emissions accounted in 2022 to 36.8 Gt (IEA 2023a), which means: the sectors depicted in the graph account for about one third of today's global CO_2 emissions.

Global marginal abatement cost curve for CO_2 from using $1/kg hydrogen, by sector in 2050

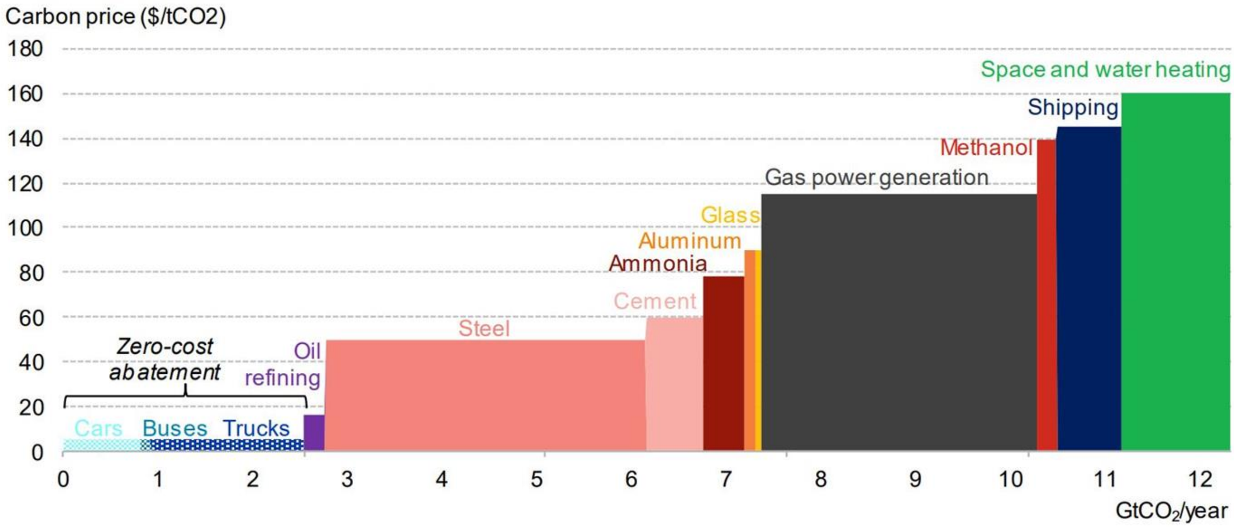


Figure 72: Global marginal abatement cost curve for CO_2 from using $1/kg hydrogen, by sector in 2050

Source: (BloombergNEF 2020a, p 6)

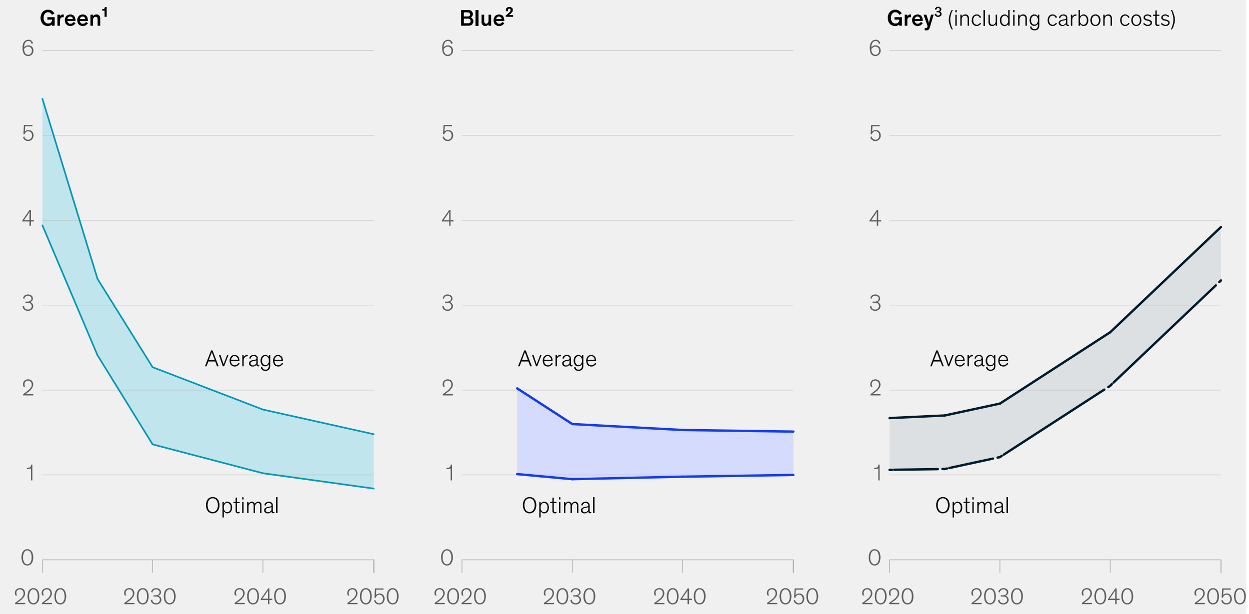
Note: Sectoral emissions based on 2018 figures, abatement costs for renewable hydrogen delivered at $1/kg to large users, and $4/kg to road vehicles. Aluminium emissions for alumina production and aluminium recycling only. Cement emissions for process heat only. Refinery emissions from hydrogen production only. Road transport and heating demand emissions are for the segment that is unlikely to be met by electrification only, assumed to be 50% of space and water heating, 25% of light-duty vehicles, 50% of medium-duty trucks, 30% of buses and 75% of heavy-duty trucks.

6.1.3 It is recommended that a similar country-specific marginal abatement cost curve be developed for CO_2, taking into account local conditions in Saudi Arabia.Production and Transport costs

Production costs

Clean hydrogen costs are expected to decline over the next decade as depicted in Figure 73. Increasing tariffs for CO_2 emission certificates will make grey hydrogen uneconomical around 2040. The graph shows quite optimistic production costs for blue hydrogen, because it is at least as expensive as grey hydrogen (without the carbon costs) since carbon capture, compression and transport of the CO_2 requires a complex infrastructure, which is quite energy intensive and costly to operate.

Production cost of hydrogen ($/kg)



[1]Based on alkaline with size classes of 2 megawatts (MW) (2020), 20 MW (2025), and 80 MW (from 2030); based on levelized cost of energy of $25–73/megawatt-hour (MWh) (2020), $13–37/MWh (2030), and $7–25/MWh (2050).
[2]Gas price of flat $2.6–6.8/million British thermal units (MMBtu); based on $30/ton CO_2 (2020), $50/ton CO_2 (2030), $150/ton CO_2 (2040), and $300/ton CO_2 (2050). Assumes autothermal reforming with carbon capture and storage and 98% CO_2 capture rate.
[3]Steam methane reforming without carbon capture. Gas price of flat $2.6–6.8/MMBtu; based on $30/ton CO_2 (2020), $50/ton CO_2 (2030), $150/ton CO_2 (2040), and $300/ton CO_2 (2050).
Source: Hydrogen Council Decarbonization Pathways; McKinsey Hydrogen Insights

Figure 73: Production cost of hydrogen

Source: (McKinsey 2022a)

Hydrogen production costs from PV and wind power systems today and in the mid- (2030) to long term (2050) are provided in Figure 74. Hydrogen produced with prices for electrical energy below $1 ct/kWh from renewables (green hydrogen) becomes the cheapest option compared to conversion from fossil fuels with (blue hydrogen) or without carbon capture (grey hydrogen).

Through 2030, hydrogen demand will grow steadily in the industry, the transport, energy, and building sectors, with cross-sectoral collaborations fostering hydrogen project developments. Hydrogen production costs are expected to decrease about 50% by 2030 and continue to decline by 2050. **By 2050, green hydrogen production costs in parts of the Middle East, Africa, Russia, China, the US, and Australia will range between $1 and $1.7/kg, while costs in regions with limited renewable resources, such as Europe, Japan, and Korea, will be around $2.2/kg, making them likely importers.** Countries such as the U.S., Canada, Russia, China, India, and Australia could develop in-country trade due to the varying competitiveness of hydrogen production in their regions. As a result, export and import centers will emerge worldwide, like current oil and gas trading centers, but with new players in regions rich in renewable energy.

Production costs of hydrogen in Germany and Saudi Arabia

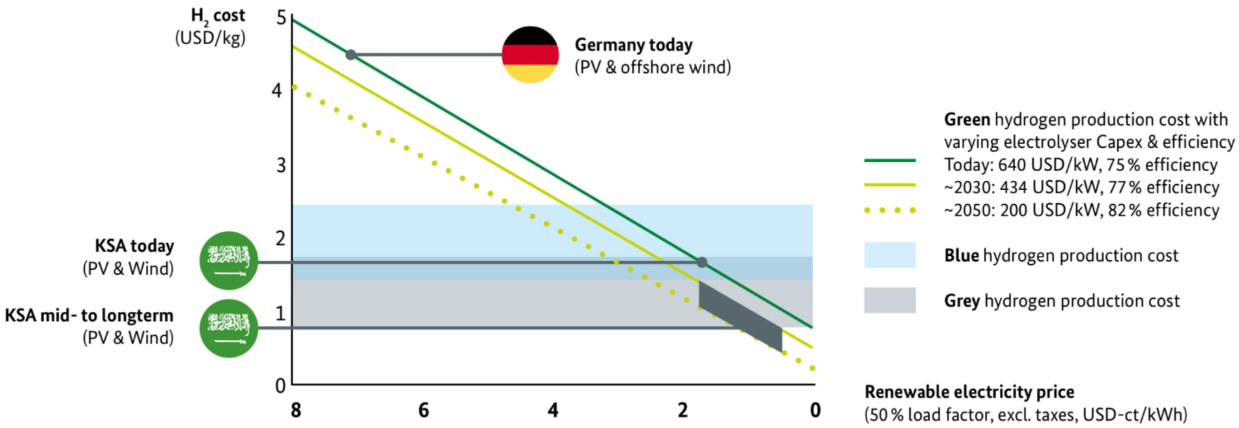


Figure 74: Production costs of hydrogen in Germany and Saudi Arabia today and mid- to long term

Source: (Guidehouse 2022b, p 10)

Note: Calculation assuming 6% WACC, 15 yr lifetime, fixed Opex 1.5% of Capex

Transport costs

The type of synthetic fuel can have a significant impact on the production costs, particularly on transportation costs to customer markets. Up to 2,600 km transport of hydrogen by pipeline is the most cost effective, and for longer transport distances, ammonia has proven to be the most competitive (compare with Figure 68).

Hydrogen production competitiveness varies across global regions. Japan and South Korea have limited competitive production resources and must rely on imports, while Central and Western Europe cannot produce the needed volumes due to capacity limitations. Production costs and commercial potential differ by region, influenced by three main factors (H2C 2022, 12ff):

1. Levelized cost of hydrogen production, driven by local renewable resources, electrolyser utilization rate, or local methane and carbon capture and storage (CCS) costs.
2. Availability and costs of other critical feedstocks, such as biogenic CO_2 for synthetic fuels or high-quality iron ore for direct reduced iron (DRI) used in green steel.
3. Country-specific factors, including investment attractiveness (market efficiency, workforce availability, or country risk) and local public acceptance of new infrastructure.

6.1.4 Supply & demand categories of regions

Three general categories of hydrogen-producing regions and consumers can be differentiated (H2C 2022, p 13):

1. High hydrogen-export potential countries:

They can reach a competitive hydrogen price below $1.15/kg, but in some cases lack demand. Examples include the Middle East, South America, and in southern African countries (e.g. Namibia and South Africa). In Saudi Arabia, there is in principle already a domestic demand for hydrogen in oil refining, ammonia and methanol production, as shown in Section 4.3.2.

2. Countries with cheap supply and large demand:

China and North America will satisfy most of their demand through competitive domestic production. In China, (grey) hydrogen costs less than $1.00/kg, while in the US, most hydrogen is under $1.15/kg.

3. Demand locations where low-cost domestic supply is limited or nonexistent:

Densely populated regions like Europe, Japan, and South Korea have expensive domestic hydrogen production, typically at least $1.80/kg or even over $2.50/kg. High costs result from land availability constraints and difficulties in developing onshore wind and solar power for global competitiveness. Decarbonization of existing power will likely be prioritized over new renewable-hydrogen production, except when hydrogen is used as a balancing tool.

6.1.5 Export potential for Saudi Arabia to its key off-taker markets.

In terms of potential future trade relation in the (green) hydrogen field the following scenarios are probable:

Saudi Arabia does present strong features to become a country of choice for hydrogen and its derivatives´ production, both for domestic and exports purposes.

Strong established trade ties with energy-hungry Asian countries place the Kingdom in an advantageous position to continue fulfilling its role as energy provider. For geography-constrained Japan and South Korea, with their (nearly) insular situation and densely populated surface, energy imports will remain high on the agenda.

China and India, the most populous countries on earth, might satisfy to some extend part of their domestic energy thirst; however, **with the speed of their economic and industrial developments, energy imports will be maintained for the time ahead**.

Second behind China in terms of exports originating from Saudi Arabia, **the EU could use its existing trade ties as well with the Kingdom and expand them to new heights.** The immense potential in addition to energy versatility unfold by Saudi Arabia, from a hydrocarbons´ but also renewables´ perspective, transform it into an ideal interlocutor in the upcoming hydrogen race.

In general, it always makes more sense to export higher value goods rather than basic commodities. For example, export of green steel will provide higher revenues than exporting green hydrogen and iron ore.

6.2 Recommendations

From a natural, industrial or infrastructural perspective, Saudi Arabia possesses many advantages to kickstart carbon-free hydrogen production and use. Among the observed countries, many will not be able to cover their domestic demand. There, based on its depicted intrinsic assets, Saudi Arabia could add hydrogen as another export success story to the existing ones.

To minimize risks, it is recommended to invest in both domestic hydrogen demand and production for export markets. Priorities for the domestic market in Saudi Arabia can be derived from Figure 72. For example, heavy transport and oil refinery are the most promising applications. Instead of using natural gas to produce hydrogen, the huge potential of renewable energy should be exploited. The lowest LCOE for power generated by wind and solar energy systems will allow competitive price levels to generate hydrogen by electrolysis from renewables.

On the other hand, hydrogen produced with renewable energies via electrolysis consumes some amount of fresh water (the stochiometric demand amounts to about 9 tons of water are needed to produce 1 ton of hydrogen). Additional seawater desalination plants are needed in Saudi Arabia, which should also be powered by renewables in the medium to long term.

CCS and CCUS are still technologically not fully mature and there are remaining risks attached to these technologies. Also, it is not based on a circular economy if the CO_2 is not permanently captured and stored, which could cause harm in the long term. Additional energy is needed to capture, compress, transport and store the CO_2 which is a clear disadvantage (as detailed in Box 1).

It seems advisable not only to invest in blue hydrogen and derivatives, but also to **substantially expand the green manufacturing pathway**. To minimize risks, different technologies should be explored. In any case, the avoided CO_2-emissions need to be traceable and certified by independent bodies. If this is not possible, simply exporting LNG would be a better solution than converting it into ammonia and shipping it to these markets.

6.2.1 RE expansion in Saudi Arabia

Electricity can be produced at very low costs by solar and wind in Saudi Arabia. A strong expansion of these renewable energy sources will help to reduce fossil fuels consumption for power generation. Additional renewable energy can be used to replace SMR production of hydrogen based on natural gas. With a combination of large RE-installed capacities and saved natural gas, Saudi Arabia has the potential to be one of the main exporters of carbon-free hydrogen and PtX.

To renew the energy system, the transport system, the building stock, in addition to industrial processes from the ground up, this requires the rapid mobilization of large amounts of capital, including for infrastructures. In this context, hydrogen has an advantage as it can link new facilities with existing infrastructure, e.g. for the transport and storage of natural gas and oil (IEA 2023b, p 19). **There, Saudi Arabia has the competitive advantage that it has the financial leverage for large investments.**

6.2.2 Product type to be exported to selected regions

Where no pipelines exist, or the distance is too long, shipping of ammonia is the cheapest option. Technologies to directly use ammonia for gen-sets, burners etc. are being developed in Japan and Europe.

The product that is consumed in the individual off-taker market needs to be considered: for example, if an Asian country expresses a demand for methanol, it would be better to produce methanol in Saudi Arabia and export it, instead of shipping liquefied hydrogen to this country. The same principle applies to ammonia or even green steel or other products consuming hydrogen.

Many countries still rely on ammonia imports for fertilizer production, and it can be expected that ammonia demand will also be one of the most relevant energy carriers in the future.

Methanol is needed to produce formaldehyde, plastics and other chemicals. It can also be relevant as an energy carrier, but it needs to be considered that when burning it, carbon dioxide will be released.

In general, the role of oil and natural gas as raw materials for high-value chemical products will continue to be important. Only their function as fossil fuels for combustion purposes will decrease, as can be seen in e-mobility. Especially if the carbon contained in the oil and gas is bound in solid products (such as plastics), no carbon dioxide is released over a longer period, so climate neutrality is not really in question.

Certifications and trustful and traceable regulations need to be in place to trade green or blue products. It is important that such procedures are established, especially for international trade. This is true for hydrogen, but also for carbon dioxide emission certificates.

The expected profit margins from hydrogen and derivatives will most likely only partially match those from oil. Therefore, new opportunities such as increased domestic added value should be explored to fill the financial gap created by lower oil sales (for combustion purposes), especially when it comes to using hydrogen directly for the production of goods with a higher value-added rather than exporting the raw materials for them to be refined somewhere else.

APPENDIX

Key Conversion Data

1 Exajoule [EJ] = 277.777 777 777 78 Terawatt hour [TWh] calorific units[6]

1 kWh H_2= 3.6 MJ H_2
1 MWh H_2 = 3.4 MMBTU H_2
1 MJ H_2 = 0.277 kWh H_2

Conversion

kWh and kg H_2:
1 kg H_2 = 33.3 kWh H_2 *(heat unit Hu /calorific value)*
1 MWh H_2 = 30 t H_2
1 Mio t H_2 = 33 TWh H_2

Production (empirical values)

To produce 1 ton of H_2 about 50 MWh of electrical energy is needed and 9 tons of fresh water.

Crude oil*	**To** tonnes (metric)	kilolitres	barrels	US gallons	tonnes/ year
From			**Multiply by**		
Tonnes (metric)	1	1.165	7.33	307.86	–
Kilolitres	0.8581	1	6.2898	264.17	–
Barrels	0.1364	0.159	1	42	–
US gallons	0.00325	0.0038	0.0238	1	–
Barrels/day	–	–	–	–	49.8

*Based on worldwide average gravity.

Oil products	**To convert** barrels to tonnes	tonnes to barrels	kilolitres to tonnes	tonnes to kilolitres	tonnes to gigajoules	tonnes to barrels oil equiv.
From			**Multiply by**			
Ethane	0.059	16.850	0.373	2.679	49.400	8.073
Liquefied petroleum gas (LPG)	0.086	11.600	0.541	1.849	46.150	7.542
Gasoline	0.120	8.350	0.753	1.328	44.750	7.313
Kerosene	0.127	7.880	0.798	1.253	43.920	7.177
Gas oil/ diesel	0.134	7.460	0.843	1.186	43.380	7.089
Residual fuel oil	0.157	6.350	0.991	1.010	41.570	6.793
Product basket	0.124	8.058	0.781	1.281	43.076	7.039

[6] https://www.convert-measurement-units.com/convert+Exajoule+to+Terawatt+hour.php

Box 6: How much hydrogen is needed to produce 1 ton of green ammonia?

Green ammonia refers to ammonia produced using hydrogen from electrolysis powered by renewable energy sources, such as solar or wind power, instead of traditional methods using natural gas or other fossil fuels. The process involves the combination of hydrogen and nitrogen using the Haber-Bosch process to produce ammonia (NH_3). The stoichiometric calculation can be found below.

To produce 1 ton (1,000 kg) of ammonia, you would need:

1. 3 moles of hydrogen (H_2) for every mole of nitrogen (N_2) in the ammonia production process, as per the balanced chemical equation:
   $N_2 + 3H_2 \rightarrow 2NH_3$

2. The molar mass of ammonia (NH_3) is approximately 17 g/mol (14 g/mol for N + 3 g/mol for H). So, 1,000 kg of ammonia is equivalent to:
   1,000,000 g / 17 g/mol = 58,824 mol of ammonia

3. Since 3 moles of hydrogen (H_2) are needed for every two moles of ammonia, one would need:
   58,824 mol of ammonia × 3 mol of hydrogen/mol of ammonia = 88,236 mol of hydrogen

4. The molar mass of hydrogen is 2.01568 g/mol. Therefore, the mass of hydrogen required would be:
   88,236 mol of hydrogen × 2.016 g/mol = 177,854 g, or approximately 178 kg of hydrogen

In summary, approximately 178 kg of hydrogen is needed to produce 1 ton of green ammonia. Be aware that this is a theoretical value that does not take into account the energy efficiency of the electrolysis process or the efficiency of the ammonia synthesis process, which may vary depending on the technologies and conditions used.

Box 7: How much hydrogen is needed to produce 1 ton of green methanol?

Green methanol refers to methanol produced using hydrogen from electrolysis powered by renewable energy sources, such as solar or wind power, instead of traditional methods using natural gas or other fossil fuels. The process involves the combination of hydrogen and carbon dioxide (CO_2) to produce methanol (CH_3OH). Here is the stoichiometric calculation.

To produce 1 ton (1,000 kg) of methanol, you would need:

1. 3 moles of hydrogen (H_2) for every mole of carbon dioxide (CO_2) in the methanol production process, as per the balanced chemical equation:
   $CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$

2. The molar mass of methanol (CH_3OH) is approximately 32 g/mol (12 g/mol for C + 16 g/mol for O + 4 g/mol for H). So, 1,000 kg of methanol is equivalent to:
   1,000,000 g / 32 g/mol = 31,250 mol of methanol

3. Since 3 moles of hydrogen H_2 are needed for every mole of methanol, one would need:
   31,250 mol of methanol × 3 mol of hydrogen/mol of methanol = 3 x 31,250 = 93,750 mol of hydrogen

4. The molar mass of hydrogen H_2 is 2.01568 g/mol. Therefore, the mass of hydrogen required would be:
   93,750 mol of hydrogen × 2.016 g/mol = 188,970 g, or approximately 189 kg of hydrogen

In summary, approximately 189 kg of hydrogen is needed to produce 1 ton of green methanol.

This is a theoretical value and doesn't take into account the energy efficiency of the electrolysis process or the efficiency of the methanol synthesis process, which can vary depending on the specific technologies and conditions used.

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