The Role of Hydrogen for the Energy Transition in the UAE and Germany

A joint study by the Emirati-German Energy Partnership

UNITED ARAB EMIRATES
MINISTRY OF ENERGY & INFRASTRUCTURE

Supported by:

Federal Ministry
for Economic Affairs
and Energy

on the basis of a decision
by the German Bundestag

Table of Contents

Imprint

Published by
Guidehouse
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www.guidehouse.com

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Print
USE Union Sozialer Einrichtungen gemeinnützige GmbH

First print run
150 copies

Date
January 2021

A. Executive Summary

The United Arab Emirates (UAE) and Germany are actively collaborating on topics regarding the energy transition through the **Emirati-German Energy Partnership, or the Energy Partnership (see chapter 1).** To assess the role of hydrogen for its energy transition and the potential for exports, the UAE founded a technical hydrogen committee. Meanwhile, Germany has adopted a national hydrogen strategy to sketch out the necessary next steps to support market uptake of low carbon hydrogen **(see chapter 2).**

The Energy Partnership commissioned this study to summarise findings of joint activities in the field of hydrogen, provide an overview on the topic, and examine future cooperation potential between the UAE and Germany.

Hydrogen production (see chapter 3). Almost all hydrogen today is produced from fossil fuels (grey hydrogen). Blue hydrogen (from fossil fuels with carbon capture and storage) and green hydrogen (from renewable electricity) are novel low carbon options. Green hydrogen can be processed further into derivatives such as methanol or gasoline. Fossil-based hydrogen (blue and grey) is cheaper than green hydrogen but dropping prices for renewables and electrolysers are expected to make green hydrogen competitive soon. Blue hydrogen is associated with higher CO_2 emissions than green hydrogen, the latter which can also lead to significant CO_2 emissions if not produced exclusively from renewable electricity.

Governments, academia, NGOs, and the private sector should work together to define sustainability criteria and effective monitoring mechanisms for green and blue hydrogen.

Hydrogen trade, transport, and storage (see chapter 4). Trading green hydrogen internationally offers revenue potential for countries with good production potential (like the UAE) and cost savings for importers (like Germany). At large traded volumes, pipeline transport of hydrogen is the cheapest option due to economies of scale in pipeline construction and a high fixed-cost share. Shipping hydrogen could be the cheapest option for smaller volumes but may still be prohibitively expensive. It would also require new infrastructure like terminals. Shipping hydrogen derivatives in contrast is significantly easier and more affordable than shipping pure hydrogen and could therefore be more attractive for trade between the UAE and Germany as long as no pipelines exist. For large-scale storage of hydrogen, the most economical option are salt caverns, which are available across Europe. For small-scale storage, more expensive tanks may be used.

Hydrogen applications (see chapter 5). The UAE has attractive preconditions for hydrogen-based steelmaking due to cheap hydrogen production potential and existing gas-based steel production facilities. Hydrogen derivatives can also replace many fossil feedstocks for chemicals (Power-to-Chem). In the energy sector, hydrogen is attractive mainly for seasonal energy storage. Hydrogen transmission may also be used to alleviate electricity grid constraints in Germany. In both countries, hydrogen and its derivatives are attractive transport fuel options. Energy efficiency dictates careful consideration into which fuel should be used for which transport option. Green hydrogen in refineries could be an attractive short-term application in both countries. Scenarios show that reaching carbon neutrality in Germany will require several 100 TWh of hydrogen and its derivatives, with major shares imported.

A close bilateral cooperation on hydrogen-related topics between Germany and the UAE can help accelerate the deployment of hydrogen (see chapter 6). This includes upstream (e.g. joint projects for green kerosene production), midstream (e.g. stakeholders from both countries to cooperate on the transport of synthetic fuels) and downstream (e.g. technology cooperation for hydrogen use in industry). German companies can provide valuable expertise to support the cooperation and provide **solutions across the hydrogen value chain (see chapter 7).**

1

Cooperation between the UAE & Germany

1.1 The Emirati-German Energy Partnership

The Energy Partnership between the United Arab Emirates (UAE) and Germany was initiated in January 2017 between the UAE Ministry of Energy and Industry (MOEI) and the German Ministry for Economic Affairs and Energy (BMWi). It promotes dialogue on topics of the energy transition between the public sector and industry from the UAE and Germany. Both countries aim to transform their energy systems to meet the targets of the Paris Agreement while guaranteeing an affordable, secure, and sustainable energy supply. The partnership creates a framework for collaboration in the fields of renewable energy, energy efficiency in buildings and industry, the development of the electricity sector, and sustainable mobility. Since the Energy Partnership's inception, bilateral activities of all kinds—from mutual delegation visits and study tours to expert workshops, excursions, and short studies—have been conducted with the aim to share technical knowledge and lessons learnt and to provide opportunities for industry. In the implementation of the Energy Partnership, BMWi is supported by Guidehouse, (formerly Navigant) and the German Emirati Joint Council for Industry and Commerce (AHK).

1.1.1 Emirati-German cooperation on hydrogen

Hydrogen will play an important role in the energy systems of the future. The Energy Partnership is working on the topic of hydrogen and its derivatives in a dedicated workstream through activities such as studies and workshops. In January 2020, the Energy Partnership held a public expert workshop on hydrogen in Abu Dhabi. The workshop was opened by H.E. Dr. Matar Al Neyadi (former Undersecretary, MoEI), Thorsten Herdan (Director General, BMWi) and H.E. Ambassador Ernst Peter Fischer (German Embassy Abu Dhabi). Around 80 experts from industry, research institutes, and public authorities were in attendance to discuss the future role of hydrogen and potential areas for cooperation. Siemens, TenneT, ADNOC, Khalifa University, Abu Dhabi Department of Energy, and Guidehouse all presented their input.

The second joint expert workshop was held in Abu Dhabi in February 2020 and focused on key enablers of international hydrogen trade. In the 2-day workshop, participants discussed transport, storage, and sustainability of hydrogen and its derivatives. The workshop served as the inaugural meeting of the newly founded UAE Hydrogen Committee. Participating organizations included the Abu Dhabi Department of Energy, ADNOC, Masdar, Emirates Water and Electricity Company, Siemens, ThyssenKrupp, IRENA, and more. H.E. Fatima Al Foora Al Shamsi, Assistant Undersecretary in the MOEI of the UAE, and H.E. Ernst Peter Fischer, Ambassador of the Federal Republic of Germany to the UAE, opened the workshop.

1.1.2 Joint study on the role of hydrogen for the energy transition

This joint study by BMWi and MOEI summarises the information the Energy Partnership gathered through the aforementioned activities. Its purpose is to present a factual overview and serve as input for future Energy Partnership activities on the topic of hydrogen.

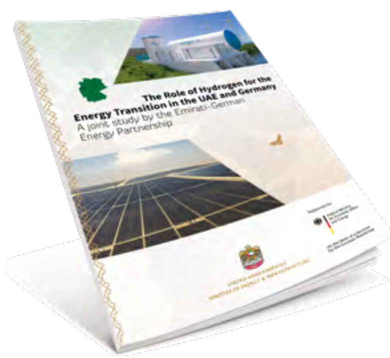

Figure 1-1: H.E. Hafsa Abdulla Mohamed Sharif Alulama, Ambassador of the UAE in Berlin. Photo: © MOFAIC. H.E. Suhail Mohamed Faraj Al Mazrouei, Minister of Energy and Infrastructure. H.E. Sharif Salim Al Olama, Undersecretary of the Ministry of Energy and Infrastructure. Photos: © MOEI

Figure 1-2: Participants of the expert workshop on International Hydrogen Trade in Abu Dhabi, February 2020, including H.E. Ambassador Ernst Peter Fischer and Fatima Al Foora Al Shamsi, Assistant Undersecretary, MOEI. Photo: © AHK Abu Dhabi

Figure 1-3: H.E. Dr. Matar Al Neyadi, Thorsten Herdan and H.E. Ambassador Ernst Peter Fischer open the public workshop of the Energy Partnership in January 2020 in Abu Dhabi. Photo: © AHK Abu Dhabi

Figure 1-4: Ellen von Zitzewitz (BMWi) at the 10th Arab-German Energy Forum hosted by Ghorfa. Photo: © Ghorfa / Mohammed El Sauaf

2

Government strategies on hydrogen in the UAE and Germany

Key Points

- Both the UAE and Germany consider hydrogen to be a key energy carrier for decarbonization.
- Germany's National Hydrogen Strategy identifies measures to promote the use of hydrogen in various sectors.
- The German Federal Government considers only hydrogen that has been produced using renewable energy (green hydrogen) to be sustainable in the long term.
- The UAE's excellent hydrogen production potential is currently leveraged for the region's largest green hydrogen project located in Dubai.

2.1 The German National Hydrogen Strategy

Figure 2-1: **Minister Peter Altmaier (BMWi) and other members of the German Cabinet present the German National Hydrogen Strategy.**

The German energy transition aims to combine security of supply, affordability, ecologic sustainability, and climate protection. Besides energy efficiency and renewable energies, the energy transition crucially depends on CO_2-free and CO_2-neutral gaseous and liquid energy carriers like hydrogen. Hydrogen makes it possible to further reduce CO_2 emissions, especially in industrial applications. The German Federal Government sees hydrogen as an important part of the future energy system.

In addition to combatting climate change, hydrogen technologies can provide future-proof jobs and new value-added potential. German companies are already well positioned in this field (for example, in electrolysis). The aim is for Germany to take a leading position in hydrogen technologies.

To accelerate the uptake of these technologies, the government supports research, funds implementation, and develops political strategies. The National Innovation Program Hydrogen & Fuel Cell Technologies has supported research on hydrogen with €700 million in funds between 2006 and 2016. The 7th Energy Research Programme, which was adopted in 2018, also promotes research activities.

To ensure that new energy technologies are implemented, the German Federal Government set up the Reallabore (regulatory sandboxes) funding line. In the first tranche, €100 million per year was made available for pilot projects from 2019 to 2022. Ten out of the 20 selected projects are related to hydrogen.

To initiate the work on political strategies in this field, BMWi has been conducting a stakeholder dialogue called Gas 2030 to discuss the role of gas in the energy transition since 2019. A key finding is that Germany will remain an energy importer in the long term.

Pursuant to the recommendations of the Gas 2030 dialogue, the German Federal Government adopted the National Hydrogen Strategy on 10 June 2020. The strategy was developed across several Ministries and aims to support the scale-up of hydrogen production and usage. In the view of the German Federal government, only hydrogen produced on the basis of renewable energies (green hydrogen) is sustainable in the long term. The strategy foresees a hydrogen demand of 90 TWh to 110 TWh in 2030. This demand will be covered by 5 GW of newly installed domestic offshore and onshore renewable energy, and by international market supply. Hydrogen's international trade and its derivatives are an important geopolitical objective.

The Energy Partnership between the UAE and Germany is built on a trusting relationship and provides an outstanding platform for exchange on hydrogen technologies and trade. Germany will cooperate closely with the UAE to unlock import potentials for green hydrogen and develop solutions that benefit both countries.

2.2 Current developments on hydrogen in the UAE

The development of hydrogen production is key for decarbonisation in the energy sector, which will result in a high demand of hydrogen globally. To respond to the possible increase in hydrogen demand—and to increase hydrogen's production and deployment—further work must be done and measures must be taken to reduce the cost of production and transportation and to ensure safety in all processes.

The UAE is rich in hydrocarbons and has a diversified energy mix, from natural gas to solar energy. This places the UAE among the top countries with potential of developing hydrogen energy further, building on the extensive experience and expertise in the oil & gas industry and in renewable energy. Hydrogen is currently among the key focus topics in R&D. Hydrogen production from hydrocarbons presents an important steppingstone, starting with grey hydrogen and transitioning to blue and green hydrogen.

One of the key pilot projects taking place in Dubai is the first solar-powered green hydrogen project. This project represents a successful government and private sector collaboration as it is being deployed by Dubai Electricity and Water Authority (DEWA) and Siemens. Through this project, DEWA aims to explore the potential of developing a hydrogen economy in the UAE.

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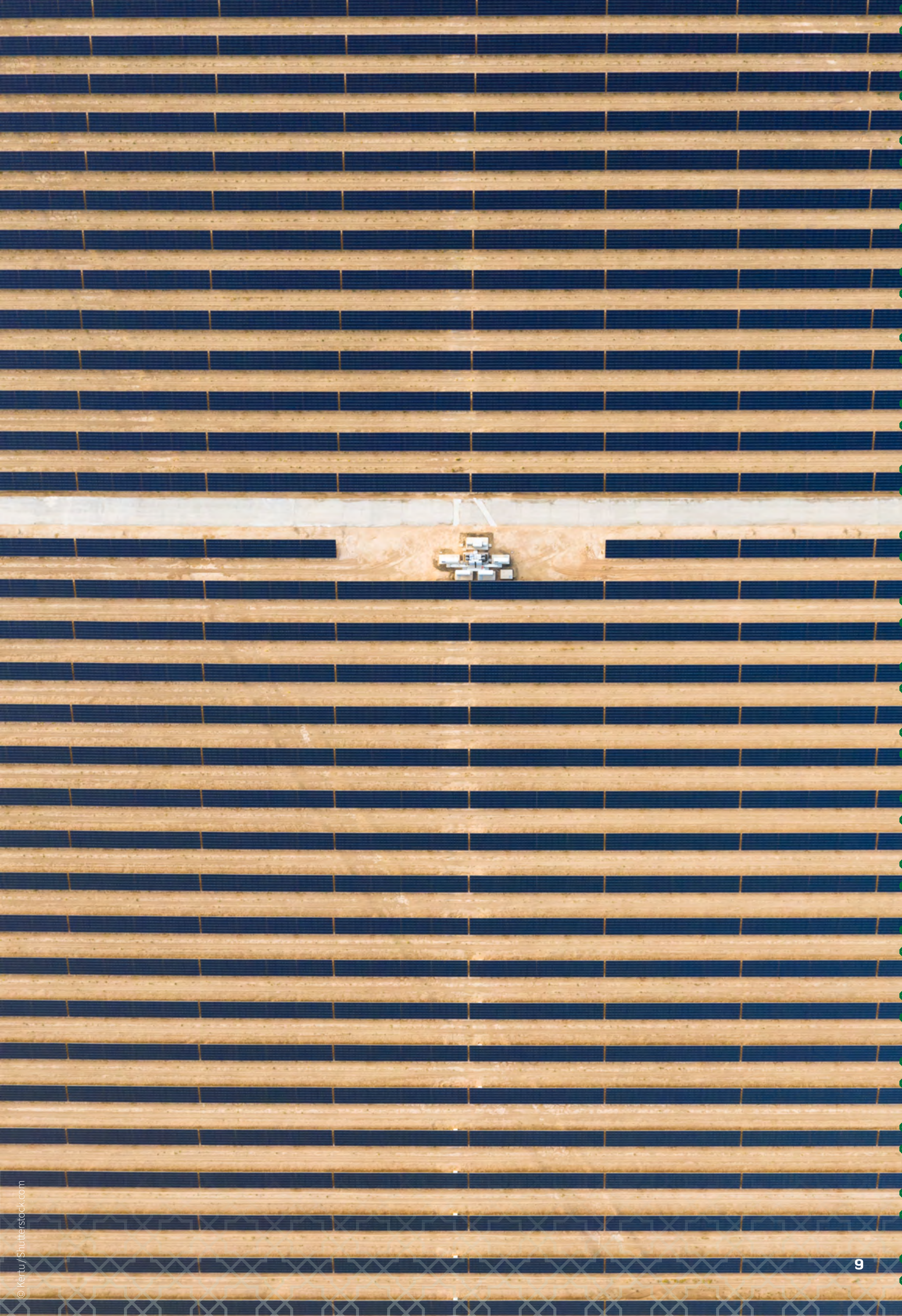
The Green Hydrogen Facility in Dubai has an area of 10,000 square metres. It aims to test and showcase an integrated, megawatt-scale plant to produce green hydrogen using renewable energy, storing the gas and delivering it for re-electrification, transportation, or other industrial uses. A test and trial phase will be conducted to ensure maximum standards of safety and reliability.

The Emirates Authority for Standardization and Metrology (ESMA) has completed the first technical regulation of hydrogen-powered vehicles in the UAE, making the UAE a pioneer in the MENA region to establish such a regulation.

The Emirati-German Energy Partnership has also been also sharing expertise between both countries to cooperate in various energy topics with a specific focus on hydrogen.
To align all the existing work in the UAE, a technical hydrogen committee has been formed.

The UAE are placed among the top countries with potential of developing hydrogen energy further



3 Hydrogen production

Key Points

- Almost all hydrogen is produced from fossil fuels today (grey hydrogen). Blue hydrogen (from fossil fuels with carbon capture and storage) and green hydrogen (from renewable electricity) are novel, low carbon options.
- Hydrogen can be further processed to derivatives such as methanol or gasoline.
- Today, fossil-based hydrogen (blue and grey) is cheaper than green but dropping prices for renewables and electrolysers are expected to make green hydrogen competitive soon.
- Blue hydrogen is associated with higher CO_2 emissions than green hydrogen.
- Governments, academia, NGOs, and the private sector should work together to define sustainability criteria and effective monitoring mechanisms for green and blue hydrogen.

3.1 Production routes of hydrogen and its derivatives

Hydrogen is produced in large quantities today. A quantity of 115 million tonnes (Mt) of hydrogen (representing approximately 3% of global final energy demand), are delivered per year, mainly for refining and ammonia production.[1] Most of the dedicated production today is based on the steam-methane reforming process (SMR), which uses natural gas to produce **grey hydrogen** (see Figure 3-1). Grey hydrogen production is a well-established technology and has a lower CO_2 footprint per unit of energy than other fossil fuels such as coal. However, these emissions are still incompatible with the Paris Agreement's objective of net zero CO_2 emissions in the second half of the century. Grey hydrogen is not discussed further in this report.

One option to produce low carbon hydrogen is to capture and store the CO_2 that is a by-product of grey hydrogen. This so-called **blue hydrogen** is in theory carbon neutral; however, in practice there are some pitfalls that can lead to significant greenhouse gas (GHG) emissions (see chapter 3.3.2). While some pilot projects are underway,[2] blue hydrogen is not yet produced in significant volumes but has the potential to become part of the transitional phase as the hydrogen economy develops.

Another option to produce hydrogen from natural gas is methane pyrolysis. The by-product of this **turquoise hydrogen** is not CO_2, but solid carbon. If the natural gas supply fulfils sustainability criteria (see chapter 3.3.2) and if the carbon is permanently stored, this would also constitute low carbon hydrogen.

An alternative to fossil fuel-based routes is hydrogen production through electrolysis, with electricity and water as feedstocks. This **green hydrogen** is carbon neutral only if the electricity used is also carbon neutral (see chapter 3.3). Electrolysis accounts for 4% of global hydrogen production today.[3] However, the current supply is a by-product originating from chlorine production, which is typically not run on renewable electricity and hence does not constitute green hydrogen. [4]

There are several green hydrogen pilot plants operational[5] and many industrial-scale projects have been announced recently.[6]

Schematic production routes of hydrogen and its derivates

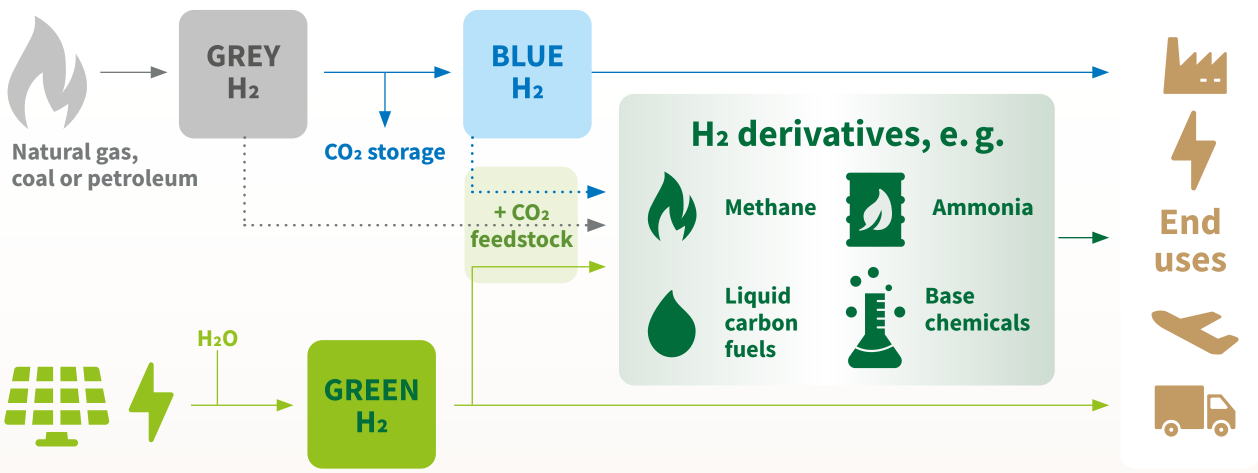


Figure 3-1: **Schematic production routes of hydrogen and its derivatives**.
Source: Guidehouse

Figure 3-1 shows the most important process routes to produce hydrogen derivatives. The most prominent examples include:

Methane

Methane can be produced with hydrogen and CO_2 as feedstocks. If it is to count as carbon neutral, the CO_2 feedstock must be renewable (see chapter 3.3). Since the transport infrastructure for natural gas is well established, electricity-based methane can be transported and used within existing energy systems. There are already operational pilots for this process in Germany.[7]

Liquid carbon fuels

Liquid carbon fuels include gasoline, methanol, diesel, or kerosene. As methane, they require CO_2 feedstock but can be transported and used like their fossil-based equivalents. This production route is often referred to as Power-to-Liquid. Some pilots are already operational in Germany.[8]

Base chemicals

Base chemicals like ethylene or propylene, which are currently petroleum-based, can also be produced from hydrogen and CO_2. This process is usually called Power-to-Chem and is discussed further in chapter 5.2.

Ammonia

Ammonia can be used as an energy carrier. The most prominent use, however, is as a base chemical, see chapter 5.2.

Hydrogen can be used as a platform molecule to produce a variety of hydrogen derivatives

These hydrogen derivatives can technically be produced from green, grey, or blue hydrogen. However, producing them from grey hydrogen using CO_2 that arises in the process would mean that the final product is not CO_2-neutral as it contains the fossil carbon atoms of the initial feedstock (e.g. natural gas). Producing them from blue hydrogen would mean that CO_2 is sequestered during the blue hydrogen production process and a different CO_2 source is needed for derivative production. In that case, it would be simpler to produce derivatives from grey hydrogen and offset the CO_2 emissions with negative emissions elsewhere. Due to these challenges with the further processing of grey and blue hydrogen, production of derivatives is discussed here only for the green hydrogen route. Ammonia is an exception in this context as it is not carbon-based.

In Figure 3-1, every conversion step shown in the green synthetic fuel route is associated with energy losses. Producing hydrogen through water electrolysis typically entails 30 % energy losses, Power-to-Liquid around 50 %.[9] As a result, large amounts of electricity are needed to produce synthetic fuels.

3.2 Cost of hydrogen production

The leading cost component of synthetic fuel production in the green hydrogen route is the electricity feedstock. In hydrogen electrolysis, for example, an estimation shows that electricity costs represent more than half of total costs if the electrolyser is operated at around 5,000 full-load hours.[10] The generation costs of renewable electricity are the main cost driver of synthetic fuel production, followed by investment costs. Transport costs are a major additional cost component, as discussed in chapter 4.

Grey hydrogen costs are driven by its energetic and chemical feedstock (natural gas) and investment costs for production assets. Blue hydrogen costs equal grey hydrogen costs plus carbon, capture and storage (CCS) in line with the process shown in Figure 3-1.

Figure 3-2 shows cost trends for grey, blue, and green hydrogen. SMR for **grey hydrogen** production is a mature technology, so no fundamental changes in technology costs are expected. The bandwidth of costs largely reflects differing natural gas prices by region. **Blue hydrogen** costs also fluctuate with natural gas prices. The incremental costs for CCS are relatively cheap due to the high concentration of CO_2 in the process gases.[11]

In contrast, **green hydrogen** production costs are expected to decline substantially due to downward trends in the two major cost blocks (see also Figure 3-2):

- Renewable power is already produced at low costs, especially in the UAE. The Al Dhafra PV tender, for example, yielded the world's lowest PV bid at US$ 1.35-ct/kWh. PV only reaches load factors of around 21 %.[12] Therefore to ensure higher electrolyser load factors, less variable renewable electricity may have to be added, like concentrated solar power, which was awarded for US$ 7.3-ct/kWh at Mohammed bin Rashid Al Maktoum Solar Park in Dubai.
- Electrolyser CAPEX is expected to substantially decrease from US$ 640/kW[13] to below US$ 200/kW in the future, mainly driven by economies of scale if annual installations in gigawatt-scale are realized.[14]

If the cost of renewable electricity production continues to decline and if electrolyser investment costs can be reduced as announced by the industry, green hydrogen is expected to reach competitiveness with blue hydrogen soon in some regions.[15] Recent modelling predicts that that, while blue hydrogen could be employed in the short-term, green hydrogen will meet most of the demand in the long term.[16] Blue hydrogen as a bridging technology would be at risk to produce stranded assets once green hydrogen is more economical, though units could be repurposed for hydrocarbon chemicals production which would also keep the process blue.

According to the National Hydrogen Strategy,[17] the German Federal Government considers only hydrogen that has been produced using renewable energy (green hydrogen) to be sustainable in the long term.

Cost comparision of green, grey and blue hydrogen

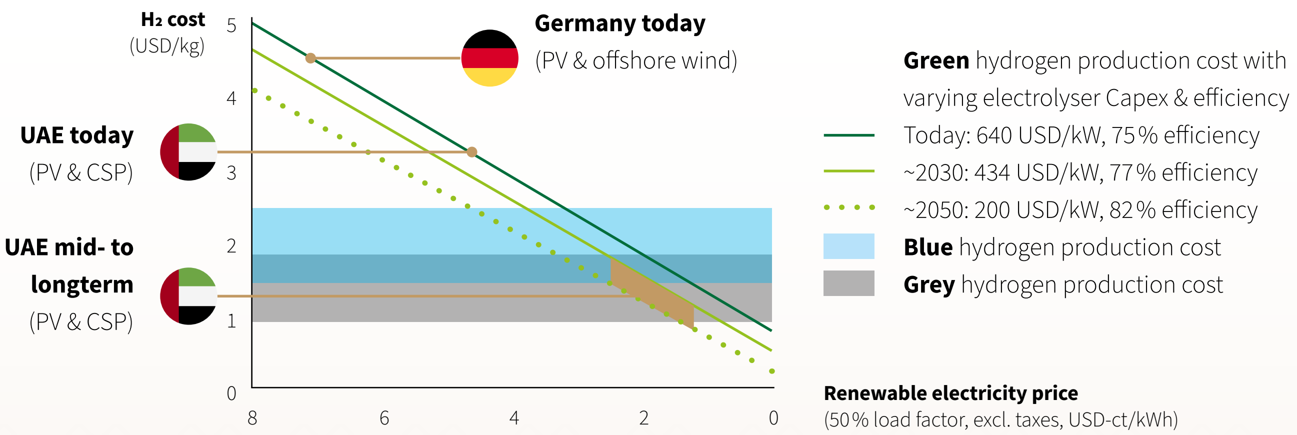


Figure 3-2: **Cost comparison of green, grey and blue hydrogen.** Source: Guidehouse and IEA (2019)
Own calculation assuming 6 % WACC, 15 yr lifetime, fixed Opex 1.5 % of Capex

3.3 Sustainability criteria for hydrogen and its derivatives

Green and blue hydrogen are not necessarily climate-friendly resources. If sourced from high-carbon electricity, they can increase CO_2 emissions. In Germany, for example, producing 1 kWh of liquid synthetic fuels with electricity from the current grid mix would emit about 780 g CO_2, which is more than 3 times higher than the 250 g CO_2/kWh emitted when conventional fossil gasoline is burned.[87] Given the UAE's more CO_2-intense grid mix, this effect would be even stronger.[88],[89] Depending on carbon sourcing and water use, hydrogen and its derivatives can lead to adverse effects for climate and environment. Figure 3-3 presents the average CO_2 emissions of various hydrogen production methods in g CO_2 per kWh H_2. Only blue hydrogen with below-average emissions and green hydrogen from renewable electricity fulfil the low carbon hydrogen criteria as set by the European Union's CertifHy standard.[90]

Sustainability criteria[91] must be developed and implemented internationally to ensure that hydrogen contributes to the fight against climate change. The participants of the first hydrogen meeting from the UAE and Germany[92] agreed that once these criteria are established, a trustworthy certification scheme with effective monitoring needs to be established to ensure that sustainability criteria are met in international hydrogen trade.

The challenge in setting sustainability criteria for all production processes and inputs will be to make them strict enough to ensure that hydrogen will enable decarbonisation and not harm the environment, but still practical enough for producers. Transitional solutions will likely play an important role in the discussions.

Given the importance of sustainability criteria for the future role of hydrogen, the discussion should be international and include governments and academia, NGOs, and the private sector.

Average CO2 emissions of hydrogen production

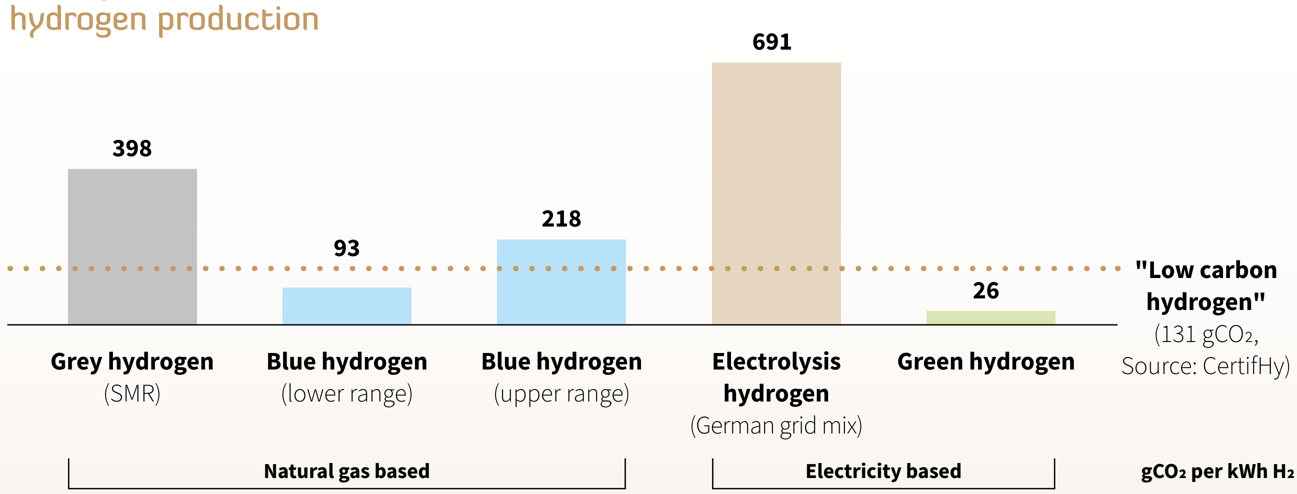


Figure 3-3: **Average CO_2 emissions of hydrogen production in g CO_2 per kWh H_2**. Source: Guidehouse, Greenpeace Energy (2020)

3.3.1 Sustainability criteria for green hydrogen and its derivatives

Electricity

The EU's Renewable Energy Directive II (RED II)[93] lays out requirements for synthetic fuel production. It demands that synthetic fuels produced on-grid be made only from renewable sources, that there be a "temporal and geographical correlation" between renewable electricity generation and synthetic fuel production, and that there be an "element of additionality" to the renewable electricity input. The last means that new renewable electricity capacities must be built for synthetic fuel production. In the case of a direct connection between renewable electricity generation and synthetic fuel production and if grid electricity is not used, it may also be counted as renewable.

These principles will be translated into a detailed, legally binding methodology by the European Union by the end of 2021. It remains to be seen to what extent the RED II criteria will serve as a blueprint for international sustainability criteria. Whether or not hydrogen produced from electrolysis powered by nuclear energy will be accepted as low carbon hydrogen in the European Union is yet to be determined.

Water

Electrolysis and other processes in synthetic fuel production require water as a feedstock. Participants of the first hydrogen meeting discussed that, beyond renewable electricity, the sustainable sourcing of water should be considered as a sustainability criterion. While Germany has relatively low water stress levels, the UAE is exposed to extremely high water stress levels.[94]

These issues can be overcome. Many attractive synthetic fuel production sites on the peninsula are located near the sea. This enables producers to source water via seawater desalination, for instance using reverse osmosis (RO) technology. The cost of installing and operating RO facilities would be a small part of overall synthetic fuel productions costs.[95] Water sustainability criteria could include obligations to use renewable energy for desalination and regulations of environmental impact from discharge water. For the long term, R&D is underway to develop electrolysers that can operate on seawater.[96]

Carbon

Synthetic fuels like methane or liquids require carbon input. There are three options to source this carbon, with varying impacts on the carbon footprint:

- Bio-based carbon would be counted as green but would likely be subject to further sustainability criteria, as for biofuels.
- Carbon from direct air capture would also be counted as green provided the energy required for the process is renewable. This technology is still at an early stage and is very expensive.
- Using carbon captured from fossil sources such as cement kilns or power plant exhausts would not be compatible with long-term decarbonisation as it still entails quarrying and ultimately emitting fossil carbon. In the short term, the technology could be employed if double counting of emission savings is avoided.[97] Prolonging the lifetime of fossil emitters due to carbon capture also needs to be avoided. There is currently no comprehensive policy framework globally or in the European Union for carbon accounting and requirements of recycled carbon fuels.

3.3.2 Sustainability criteria for blue hydrogen

Upstream emissions of methane

Methane has significant upstream emissions that come from the energy needed for sourcing, methane leakage, purification, and transport, including liquefaction and regasification.[98] These need to be drastically reduced and transparently monitored to produce low-carbon blue hydrogen.

Carbon capture rate

The carbon capture rate, which describes the captured fraction of CO_2 emissions, varies depending on the process but never reaches 100%. SMR plants coupled with CCS can capture 55-90% of CO_2.[99] The higher figure is for capture of both combustion CO_2 and output stream CO_2. Carbon capture rates of up to 90% can be reached with autothermal reforming (ATR) plants, but this technology has not been applied on a large commercial scale.[100]

The lack of experience with CCS contributes to uncertainty on actual carbon capture rates. In September 2019, the International Energy Agency counted only 19 CCS projects globally, including two that are used for blue hydrogen production.[101]

CO_2 leakage from CCS reservoirs

CO_2 would have to be stored underground for long periods of time; however, there is a risk of CO_2 leakage. Optimistic estimates put emissions from CO_2 leakage at 3 g CO_2 equivalent per MJ H_2. At an Energy Partnership workshop,[102] industry experts also remarked that enhanced oil recovery (EOR) is associated with underground CO_2 retention of 30%-90%. EOR may therefore not be able to fulfil GHG criteria for low carbon hydrogen in many cases.

CO_2 storage that would be done anyways (for example, at EOR facilities already using CO_2) should not count towards CO_2 savings. Otherwise, there would be a reallocation of negative emissions on the balance sheet without new negative emissions offsetting those from hydrogen production.

4 Hydrogen trade, transport and storage

Key Points

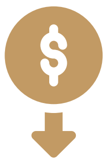
- Trading green hydrogen internationally offers revenue potentials for countries with good production potentials (the UAE) and cost savings for importers (Germany).
- Hydrogen's pipeline transport is economical for shorter distances and at large traded volumes due to economies of scale in pipeline construction and a high fixed-cost share.
- Shipping hydrogen is cheaper than pipelines for smaller volumes and longer distances but may still be prohibitively expensive. Shipping hydrogen derivatives may be preferred, especially in cases where such derivatives are demanded by end users.
- If hydrogen derivatives are required, it makes sense to produce them close to hydrogen production facilities as their transport is significantly easier and cheaper than for pure hydrogen.
- The most economical option for large-scale storage of hydrogen are salt caverns, which are available across Europe. For small-scale storage, more expensive tanks may be used.

4.1 International hydrogen trade

The global energy system is heavily based on international trade. Germany imported 72 % of its primary energy consumption in 2019.[18] In light of such a pronounced import dependency, it is likely that Germany will continue to be an energy importer in a decarbonised future. The German National Hydrogen Strategy states that most of the hydrogen needed in Germany will have to be imported.[19]

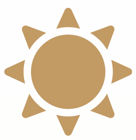
To realize such large-scale renewables trade, molecular energy carriers such as hydrogen and its derivatives are likely vectors. Molecular energy carriers have better economics over longer distances compared with electricity lines and they will likely be demanded by energy end users (see for example chapters 5.3 and 5.5).

Besides being a necessity for decarbonised energy systems, trading renewable energy internationally brings the following benefits for involved parties:



Cost benefits. Renewable energy supply from countries with cheap production potentials (such as the UAE, see chapter 3.2) can reduce costs of the energy transition for importing countries.

Volume benefits. Technically, Germany could cover its long-term renewable electricity demand domestically. The technical potential for renewable electricity is estimated at 7,800 TWh per year, much higher than total net electricity consumption of 526 TWh (2018).[20] However, land use by agriculture and settlements means that many potential sites can in reality not be used for renewable energy generation. The actual renewable potential is therefore much lower at around 800 TWh.[21] Most scenarios expect large shares of synthetic fuels will be imported (see chapter 5.5).

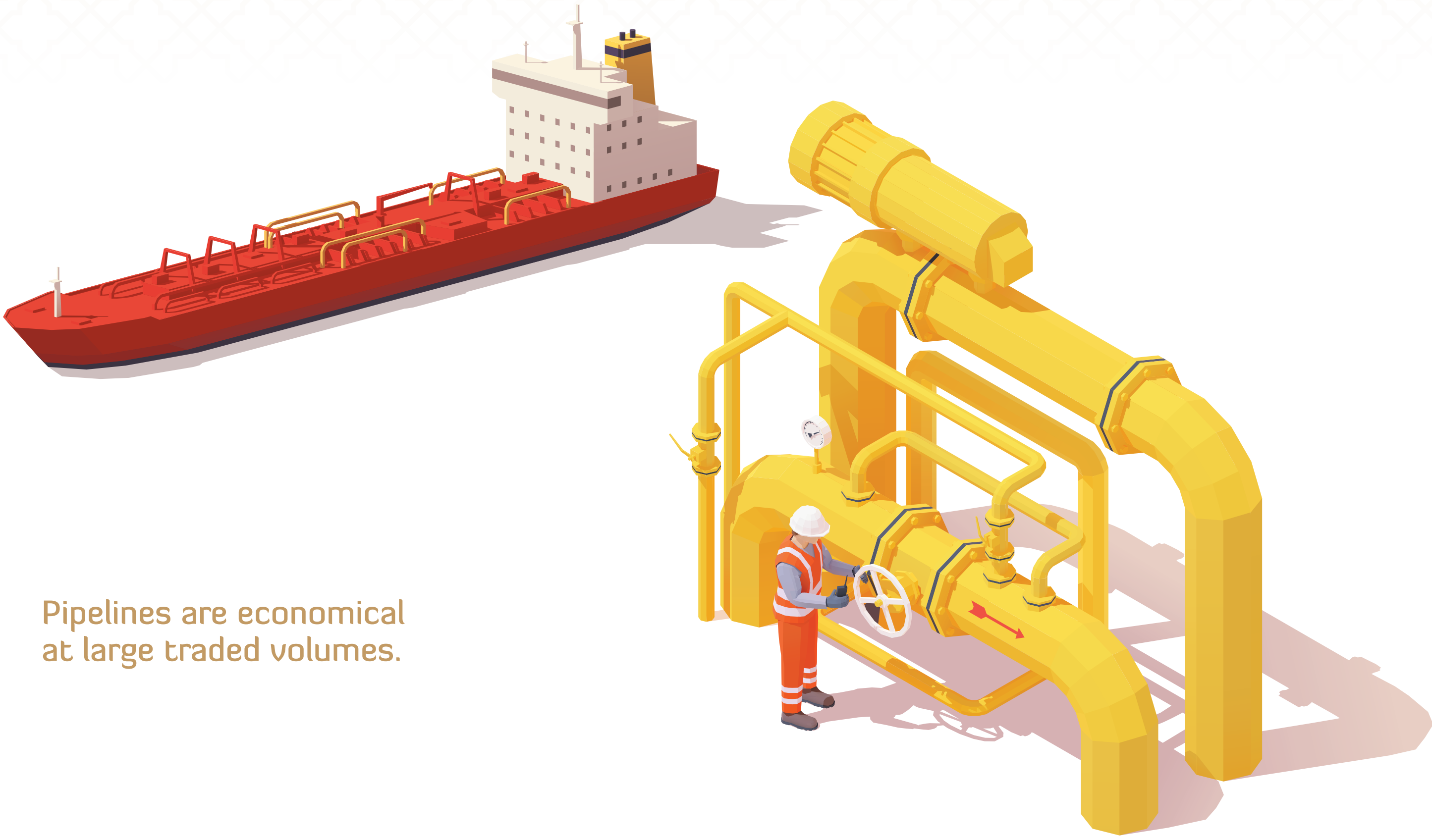


Seasonal benefits. There are structural differences between regions in electricity supply and demand over the year. Central and northern Europe experience the highest demand in winter due to heating, while countries in the MENA region typically have peak demand in summer when cooling consumes large amounts of energy. International trade of renewable energy could match these complementary patterns, leading to better resource utilisation and lower system costs.

Diversification benefits. Most Gulf Cooperation Council (GCC) countries benefit from fossil energy exports. Exports of crude petroleum, refined petroleum, and petroleum gas accounted for 48.6 % of the UAE's total exports in 2017.[22] Exporting synthetic fuels could diversify exports in the short term and compensate partly for shrinking oil exports in the course of long-term decarbonisation.

A main obstacle for international synthetic fuel markets is the so-called "chicken-and-egg" problem: potential producers will only start investing if there are secure demand markets but potential consumers will only commit to significant synthetic fuel usage if they are confident that there will be cheap, large-scale supply. Higher costs of synthetic fuels compared to fossil fuels (see chapter 3.2) will likely hinder the emergence of such a market by its own. Governments around the world should therefore enter a dialogue to trigger the creation of international synthetic fuel markets (see chapter 6).

4.2 Pipelines and shipping



Pipelines are economical at large traded volumes.

The formation of international hydrogen and synthetic fuel markets requires the reliable, economic transport of these energy carriers. While there is no single best option for this, some key parameters and what they mean for the choice of the best synthetic fuel transport option can be established.

4.2.1 Pipelines

Hydrogen can be transported either by blending it into natural gas pipelines or by building dedicated hydrogen pipelines. Blending can currently be done at a rate of up to 2%. Blending ratios of up to 10% are also possible without major effects on distribution networks or end users.[23] However, blending would reduce the value of hydrogen to the much lower value of natural gas. Another downside is that some off-takers cannot flexibly adjust to varying shares of hydrogen in the gas mix. It is not an option to linearly ramp up hydrogen content in the gas grid.

Dedicated pipelines are therefore needed to transport pure hydrogen. New hydrogen pipelines could be constructed with investment costs roughly 20% higher than those of natural gas pipelines.[24] Alternatively, existing natural gas pipelines could be retrofitted. Pipeline material, compressors, seals, and fittings would need to be overhauled, leading to cost savings of around 50% compared to newly built hydrogen pipelines.[25]

Pipelines are economical at large traded volumes due to economies of scale in pipeline construction and a high fixed-cost share. Hydrogen pipelines would therefore only be feasible if the trading partners commit to large trade volumes upfront.

4.2.2 Shipping

Hydrogen could also be transported over long distances by ships. Since space demand for shipping is a key driver for shipping costs, energy density is an important parameter to examine. The energy density of liquid hydrogen is almost twice as high as that of gaseous hydrogen under 700 bar pressure (see Table 41). Hydrogen liquefies at its boiling temperature of -253°C, which is much lower than that of natural gas (-162°C). The process of liquefication consumes approximately one-third of the hydrogen's energy content.[26] Furthermore, as much as 6% hydrogen loss can occur by "boil-off" in loading and unloading of liquid hydrogen.[27] The cost of shipping hydrogen is determined by the one-time energy and material loss rather than the shipping distance.

In contrast to shipping, the cost of pipeline transport correlates with distance in a linear fashion; for every kilometre of distance, 1 km of pipeline needs to be built. Longer trade distances make one-time conversion losses economically less relevant than variable costs per kilometre. At a certain distance, the cumulated costs for pipeline construction exceed the costs induced by energy losses for liquefication (see Figure 4-1). The distance of the breakeven point between pipelines and shipping is still debatable. The International Energy Agency estimates it to be around 3,500 km.[28] Due to the high cost uncertainty, it is not yet proven whether transport via ship or pipeline will be cheaper to transport hydrogen between the UAE and Germany.

An advantage of shipping is that it is suitable for smaller volumes than pipeline transport. Shipping import terminals require less upfront investment than pipelines. While the investment costs of Nord Stream 1, for example, were US$ 390 million per bcm capacity,[29] liquefied natural gas (LNG) import terminals are associated with investment costs in the order of magnitude of US$ 100 million per bcm capacity.[30,31] The lower upfront cost means that an import terminal is economically less dependent on maximized utilisation than a pipeline. LNG terminals are also less dependent on scale advantages, as the example of LNG shows: the largest current LNG terminal in Europe is Grain (UK) with an import capacity of 27.5 bcm per year, significantly less than Nord Stream's 110 bcm per year.[32] In Germany, LNG terminals are planned for e.g. in Brunsbüttel.

Carbon-neutral hydrogen vessels still must be developed. Kawasaki launched the world's first liquefied hydrogen carrier in late 2019, which is powered with diesel.[33] R&D is needed to build a vessel that is powered by hydrogen or another carbon-neutral fuel. Ideally, the boil-off hydrogen would be used as a fuel, as is being done for LNG. Investment costs for the vessels are not know yet because there is no such ship operational so far.

Cost of hydrogen transport via pipeline and ship

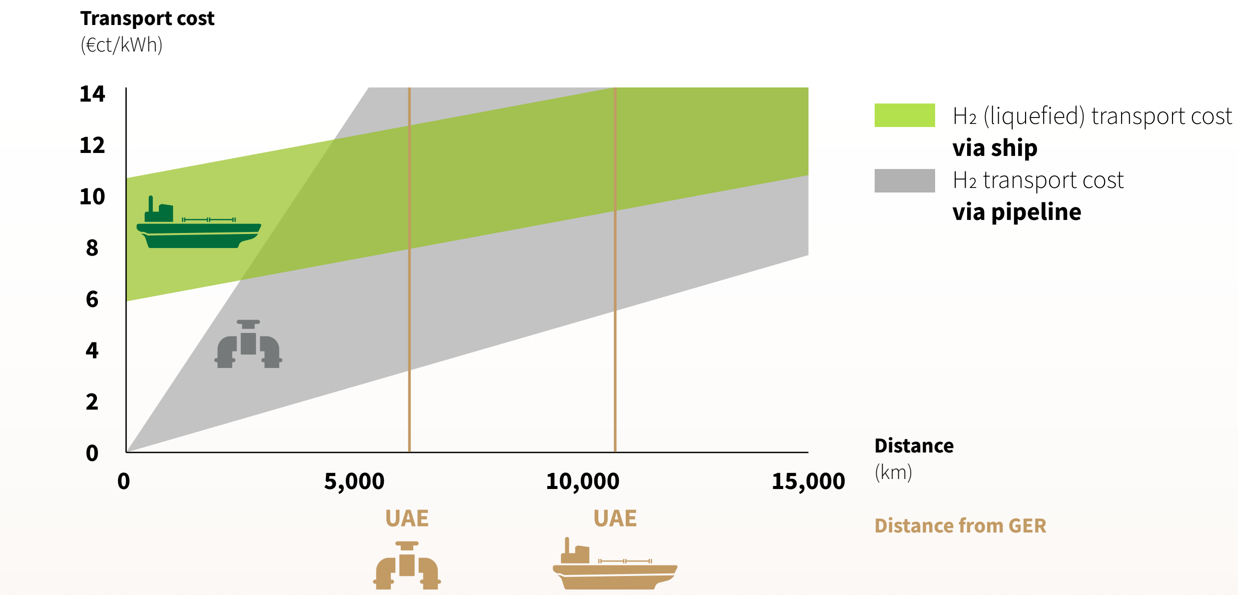


Figure 4-1: **Cost of hydrogen transport via pipeline and ship.**
Source: Guidehouse (2020): European Hydrogen Backbone. Available online: https://gasforclimate2050.eu/publications/ and IEA (2019)

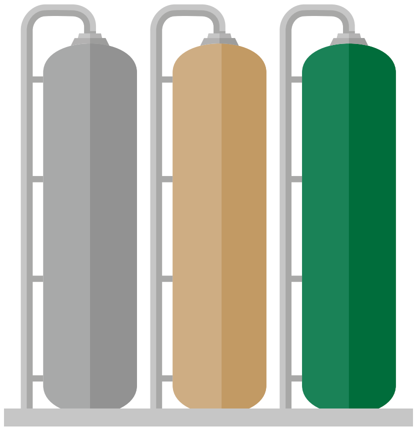
4.2 Transporting hydrogen derivatives

Hydrogen derivatives are easier and cheaper to transport than hydrogen because they have a higher volumetric energy density (see Table 4-2), are less volatile, and are easier to contain than hydrogen. In the case of methane and ammonia, the energy requirement for liquefaction is also significantly lower than for hydrogen. Like their fossil counterparts, hydrogen derivatives can be transported via pipeline, ship, railway, or truck, depending on the type of derivative and transport distance.

Hydrogen derivatives like ammonia could be used either directly as fuels or as carrier molecules. Due to its high toxicity, ammonia must be handled with care. There are also liquid organic hydrogen carriers (LOHCs) that serve the sole purpose of facilitating transport. For example, hydrogen can be reacted with organic molecules like toluene to form an easy to transport, oil-like liquid. An important issue in using LOHCs is the need to either return the transport molecule for reuse, which incurs cost and emissions, or to otherwise dispose of the chemical without returning it.

In practice, hydrogen would be converted to one of its derivatives for transport and reconverted to hydrogen upon arrival at its destination. The downside is high conversion losses of derivative production (see chapter 3.1). Hydrogen derivatives as carrier molecules only make sense economically for long distances, where the lower transport cost per kilometre outweighs the higher energy loss incurred by conversion and reconversion as well as any additional costs to return the transport molecule.

Hydrogen derivatives will be demanded by end users such as in transport (see chapter 5.4). In that case, derivatives should be produced close to hydrogen production to benefit from better transport properties (see Table 4-2). As large-scale hydrogen production facilities will be located where cheap electricity is available, these locations will also allow for cost-competitive production of hydrogen derivatives. Coupling their production to hydrogen production facilities rather than transporting hydrogen to produce derivatives in the importing country saves cost and effort.



Energy density of hydrogen derivatives

	Energy density (MJ per L)
H_2 1 bar	0.01
H_2 700 bar	5.3
H_2 liquid	10.0
NH_3 liquid	15.3
LNG	22.2
Gasoline	34.2

Table 4-2:
Energy density of hydrogen derivatives in MJ per L.
Source: Ronnie Belmans (2019)

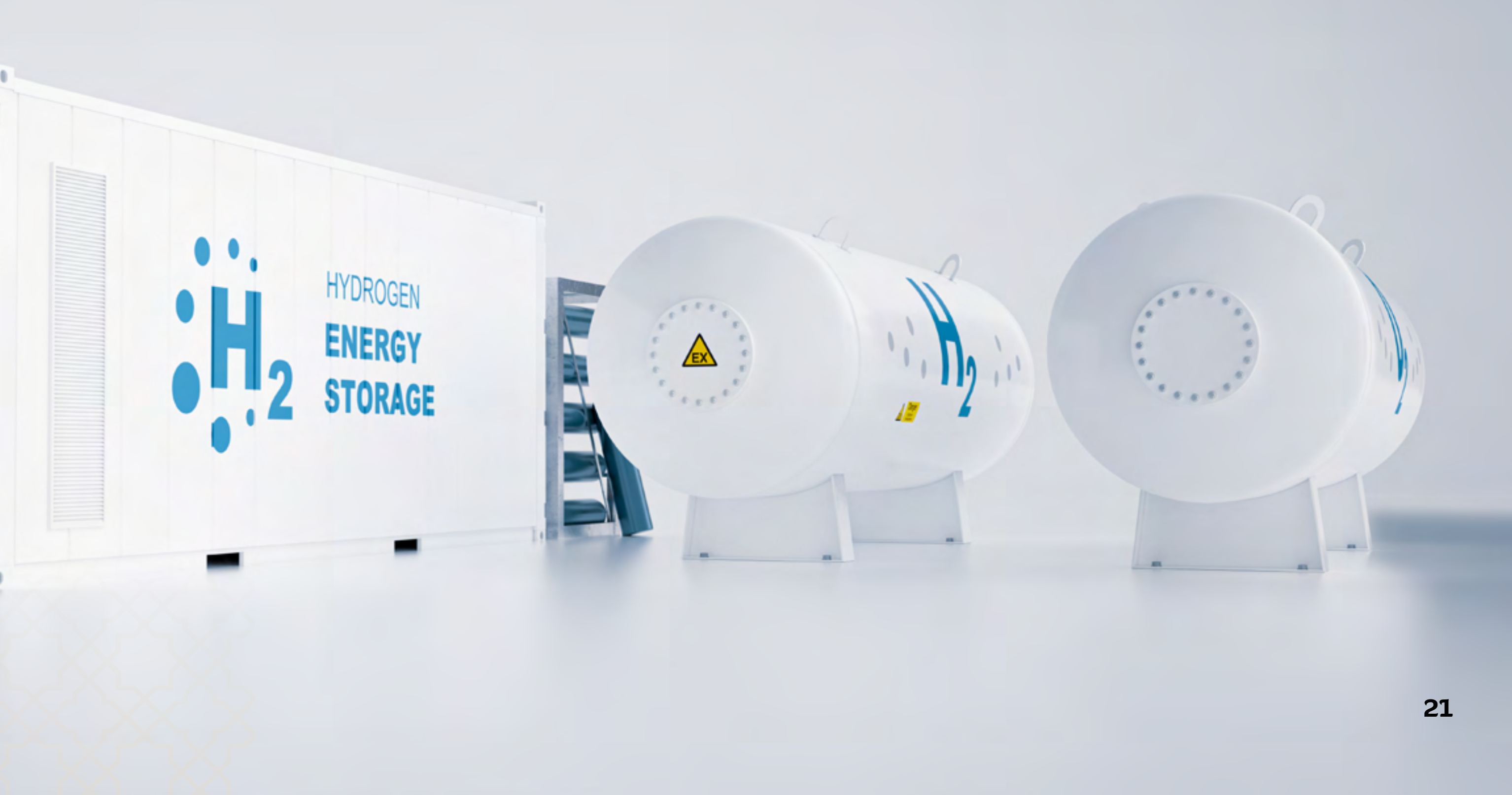
4.3 Storage options

Large-scale hydrogen markets will necessitate significant storage capacities. These would mainly be needed to bridge potential seasonal shifts between hydrogen production and consumption. There is however also an aspect of security of supply to this: EU law requires member states to hold strategic petroleum reserves lasting for 90 days of average consumption so that a potential interruption of petroleum imports can be endured.[34] If hydrogen is to be imported structurally at large scale – as petroleum today –, strategic reserves will be needed to warrant security of supply as well.

Salt caverns are currently the most promising option for large-scale hydrogen storage. These geological salt formations are large domes in the ground that can be found in many regions around the world and are being used already as natural gas storage in Germany, France, and the US.[35] Each cavern typically holds a volume of 105 to 106 m^3, which corresponds to energy content of 25 GWh to 250 GWh, assuming hydrogen at 100 bar.[36] Cavern storage sites can be installed in depleted mining sites or by digging new cavities into the salt layers. Industry estimates of investment costs for a storage site are in the order of magnitude of €50/m^3.[37]

Tanks are another proven option for hydrogen storage, which are widely used for industrial gases today. Because of hydrogen's high permeability and explosiveness, there are special requirements for the material used. This leads to high construction costs of around US$ 3,000–9,000 per m^3 liquid hydrogen.[38] Adjusted for the higher density of liquid hydrogen compared to the gas at 100 bar and converted to euros, this still means a price that is 6 times higher for tank storage than for salt caverns. Tank storage is expected to be used for smaller, decentralised storage, like at refuelling stations, while salt caverns will be employed for utility-scale storage.

The most economical option for large-scale storage of hydrogen are salt caverns. For small-scale storage, more expensive tanks may be used.



5 Hydrogen applications

Key Points

- The UAE has attractive preconditions for hydrogen-based steelmaking due to cheap hydrogen production potentials and existing gas-based steel production facilities. Hydrogen derivatives can also replace many fossil feedstocks for chemicals (Power-to-Chem).
- In the energy sector, hydrogen appears to be attractive mainly for seasonal energy storage. Hydrogen transmission may also be used to alleviate electricity grid constraints in Germany.
- In both countries, hydrogen and its derivatives are attractive transport fuel options. Energy efficiency dictates careful consideration of which fuel should be used for which transport mode.
- Green hydrogen in refineries could be an attractive short-term application in both countries.
- Scenarios show that reaching carbon neutrality in Germany will require several 100 TWh of hydrogen and its derivatives, with major shares imported.

5.1 Applications in the steel industry

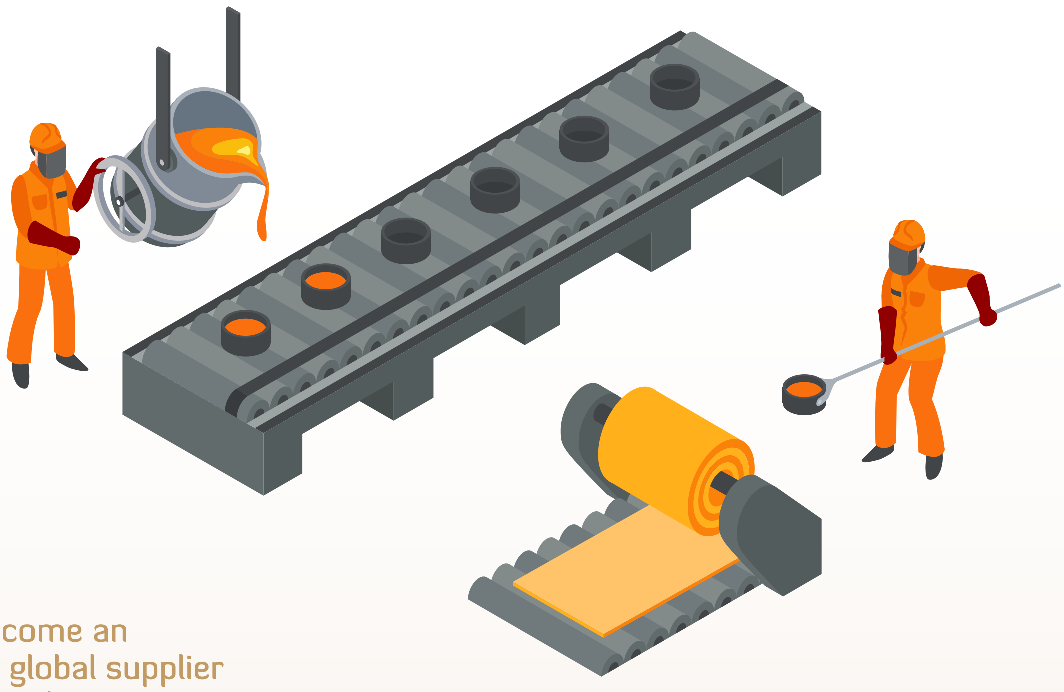
Germany is the world's seventh largest crude steel producer (43.4 Mt in 2017), the UAE ranks at thirty-eighth with 3.3 Mt.[39] The steel industry is responsible for 7%–9% of global GHG emissions, mostly stemming from the use of coking coal in the blast furnace process.[40] This has forced the industry to increasingly investigate GHG-neutral processes, most prominently direct reduction (DRI) and CCS.

The DRI process uses green hydrogen as a reducing agent instead of coal, leading to 97% GHG reduction compared to blast furnaces. Assuming €5.04/kg green hydrogen customer price (close to German production costs today, see chapter 3.2), the GHG abatement cost is estimated at €144/tCO_2. At €2.78/kg hydrogen (close to UAE production costs today), abatement costs drop to €85/tCO_2.[41]

CCS is associated with abatement costs of €60/tCO_2 to €110/tCO_2.[42] It remains to be seen whether green hydrogen cost reductions (as Figure 32 shows) will suffice to make DRI a preferred decarbonisation option for the global steel industry economically. Sustainability considerations for blue hydrogen (see chapter 3.3.2) would also need to be considered for CCS-based steel. In Germany, public acceptance for CCS is low and leading steel producers like ThyssenKrupp are advocating hydrogen-based routes instead. By contrast, in the UAE, the world's first steel CCS project went online in 2016.[43]

An important difference between steel production in the two countries is that coal-based blast furnaces account for almost all of German primary steel capacity, while Emirates Steel in the UAE uses a natural gas-based DRI process.[44] German steel-makers need to decide whether to re-invest in a blast furnace or in a new DRI facility. In the UAE, green hydrogen could be blended into the existing DRI processes, gradually replacing natural gas and thereby decarbonising the production. Together with the attractive hydrogen production potentials described in Figure 3- 1, this could be an opportunity for the UAE to become an early adopter and global supplier of GHG-neutral steel.

However, even if hydrogen-based steelmaking is the most economical option for GHG-neutral steel, it is still more expensive than conventional, GHG-intensive steel. Governments may need to support the creation of markets for GHG-neutral steel initially, through obligations for car manufacturers to use such steel or through corresponding policies in public construction projects, among others.[45]



The UAE could become an early adopter and global supplier of GHG-neutral steel

5.2 Applications in oil processing and base chemicals

5.2.1 Refining processes

Refineries are among the largest hydrogen consumers today, using it mainly for hydrocracking and desulphurisation (see chapter 3.1). Consequently, using electricity-based green hydrogen instead of grey hydrogen does not require a fundamental change of production processes or infrastructure. Refineries could begin blending small amounts of green hydrogen into existing streams of fossil-based hydrogen, leaving all other processes unchanged. The share of green hydrogen could then be increased over time.

Green hydrogen in refineries is a short-term business case due to existing regulations. The EU's RED II[46] allows conventional fuel suppliers to count green hydrogen that is used as intermediate product to reduce the share of biofuels they are obliged to blend into the fuels they sell. In cases where biofuels from food waste (for example) are not available, it might be more economical for fuel suppliers to use green hydrogen rather than more expensive biofuels.

Refinery operators in Germany are already piloting green hydrogen; among these operators are BP (Lingen refinery) and Shell (Rheinland refinery). For refinery operators in the UAE, it could also be an opportunity to become suppliers of green hydrogen-based conventional fuels for consumers in Europe. With significant refining capacities from companies like ADNOC or ENOC (see Table 5-1) and highly competitive green hydrogen production potentials (see chapter 3.2), the UAE could be in a strong position to seize this opportunity.

5.2.2 Replacing petrochemicals

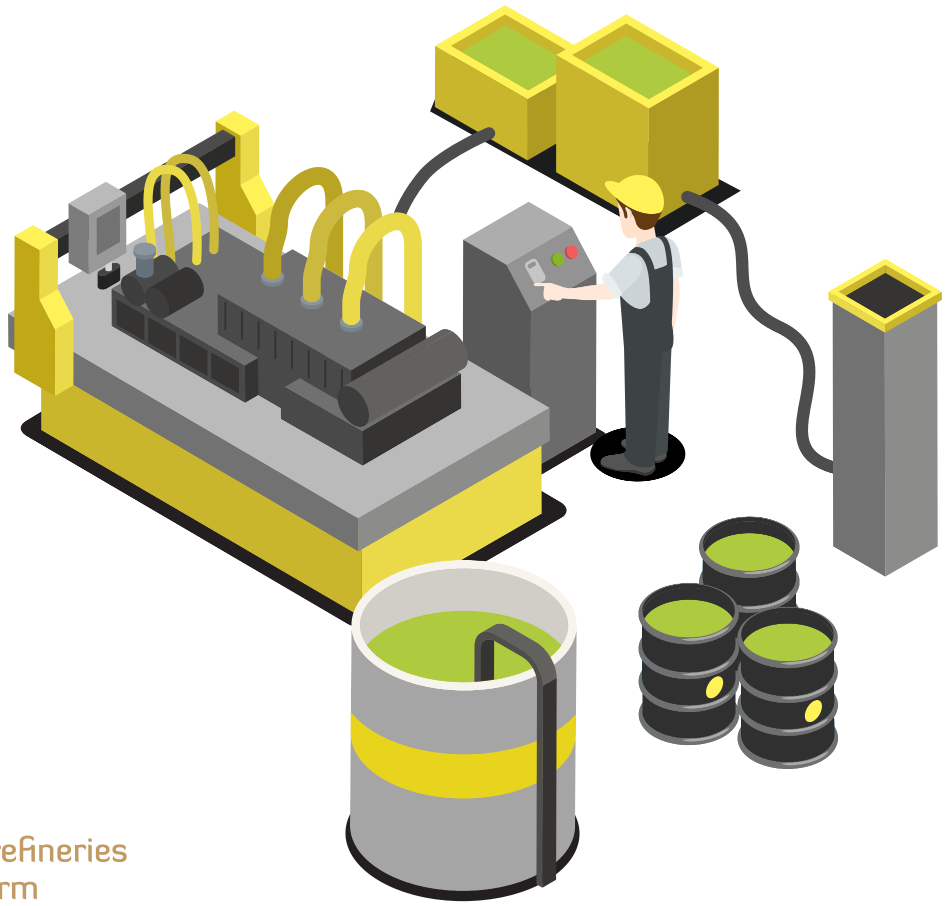
As Figure 3-1 shows, green hydrogen can decarbonise the chemical industry by replacing current fossil oil-based feedstocks. In this Power-to-Chem process, green hydrogen reacts with CO_2 to produce methanol. This methanol is further processed to olefins which are mainly used for plastics production (Methanol-to-Olefins, "MtO"). Aromatic compounds like benzene or toluene can also be derived (Methanol-to-Aromatics, MtA), opening up the full range of products that are produced from petrochemicals today.[47]

An early example for this technology is the Carbon2Chem® project in Duisburg, Germany.[48] A consortium including ThyssenKrupp, BASF, Covestro, Linde, Evonik, and Siemens is investigating how steel furnace exhausts can be converted to high value chemicals. In the longer term, the carbon source will need to be renewable (see chapter 3.3.2).

The main issue with Power-to-Chem is its high costs. Abatement costs of over €250/tCO_2 are 10 times higher than the 2019 industrial CO_2 price in the European Union.[49] This means that plastic waste recycling is economically much more attractive. However, even a drastic increase in recycling will not be able to meet total demand, so virgin base chemical production will still be needed. Power-to-Chem may be needed in the long term.[50]

	Ammonia production (2012)[51]		**Oil refinery throughput (2018)**[52]		**GDP (2018)**[53]	
	kt	% of world total	k barrels per day	% of world total	Billion USD	% of world total
UAE	**330**	**0.2%**	**1,044**	**1.3%**	**414**	**0.5%**
Germany	**2,823**	**2.1%**	**1,775**	**2.1%**	**3,948**	**4.6%**

Table 5-1: **Ammonia production, oil refinery throughput and GDP in the UAE and Germany.**
Sources: U.S. Geological Survey (2013), BP (2019), World Bank (2020)



Green hydrogen in refineries could be a short-term business case

Another downside is the enormous green electricity demand. For the European chemical industry, reducing 84 % of business-as-usual GHG emissions with Power-to-Chem in 2050 would require 1,900 TWh of green electricity,[54] a massive amount considering that total net electricity generation in 2017 in the European Union was 3,100 TWh.[55]

The UAE could be in a better position to pioneer Power-to-Chem, in part because of its large and cheap renewable electricity potentials. The chemical industry is an intricate network of complex processes, so regions with existing chemical industries will have a competitive edge when adopting Power-to-Chem. Due to the availability of petrochemical feedstocks, the UAE already has significant and growing chemicals production capacities.[56] Pioneering Power-to-Chem could be an opportunity for countries on the Arabian Peninsula.

5.2.3 Ammonia

Ammonia is a major grey hydrogen consumer today (see chapter 3.1). Decarbonising this sector can be achieved by using blue or green, instead of grey, hydrogen. Using green hydrogen is associated with high CO_2 abatement costs of €110/tCO_2–€360/tCO_2 (assuming a hydrogen price of €2.8/kg–€5.0/kg),[57] while CCS is estimated to cost €60/tCO_2 to €110/tCO_2.[58] Whether green hydrogen will play a role in decarbonising ammonia production depends on green hydrogen price reductions and the availability of CCS. In 2020, a GW-scale green hydrogen and ammonia project in NEOM, Saudi Arabia was announced with the German company ThyssenKrupp Industrial Solutions as electrolyser supplier.[59] Germany and the UAE both produce ammonia at industrial scale. Volumes in the UAE are limited (see Table 51), however green ammonia could be an opportunity to scale up this industry.

5.3 Applications in the energy sector

Synthetic fuels, especially hydrogen, are a potentially important part of electricity systems with high shares of renewable energy. Specifically, hydrogen can play a role in short- and long-term storage, reduce the need for grid expansion, and be used for space heating.

5.3.1 Short-term storage

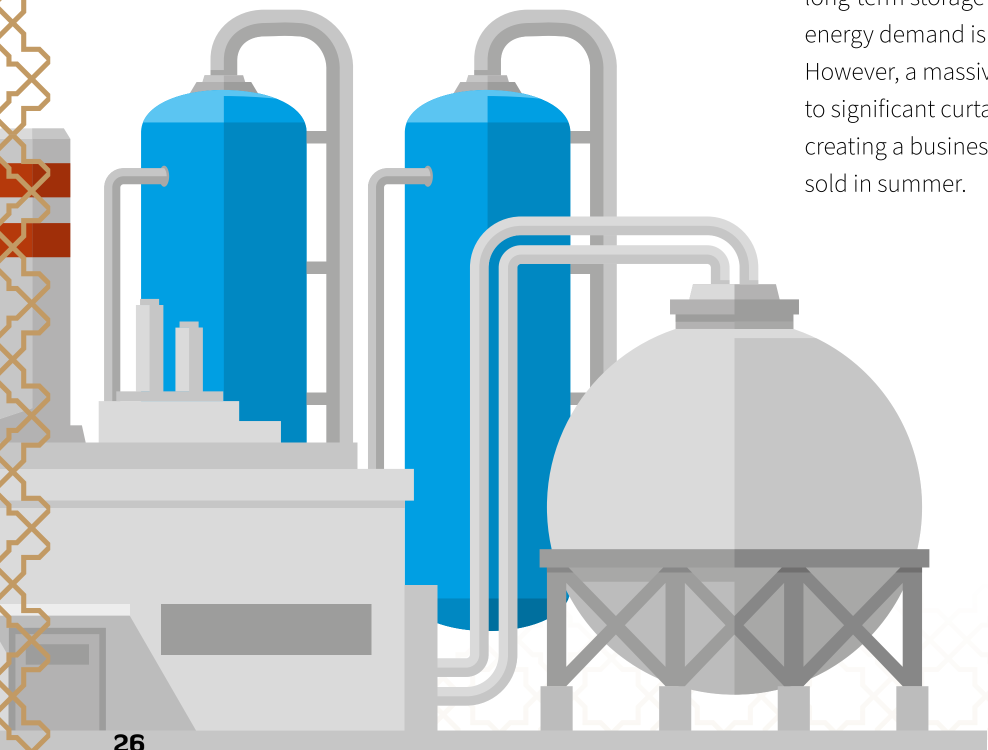
Highly renewable electricity systems will need short-term storage technologies to bridge variability in renewable infeed and consumption. Since the UAE is expected to rely predominantly on solar energy, there is also a need to determine how to cater to electricity demand at night. Hydrogen could do this, being produced during the daytime using solar electricity and then being re-electrified at night. However, batteries are a competing technology that offer round-trip efficiencies of around 90%, while electrolysis with fuel cell re-electrification stands at approximately 40%.[60] For short-term storage with many charge-discharge cycles per year, batteries could be more attractive in most cases. Countries on the Arabian Peninsula are also starting to deploy solar thermal plants as additions to solar PV, because this technology can readily incorporate thermal storage for electricity production at night.[61]

5.3.2 Long-term storage

A crucial point of long-term storage economics is that there are in many cases only a few charge-discharge cycles per year. In contrast to short-term storage, investment costs per unit of storage capacity are an important cost driver besides conversion efficiencies. Battery technologies are currently deemed to be less economical than hydrogen for storage times longer than one to four days.[62] Also, depending on the battery chemistry, significant self-discharge of storage batteries can occur over time, reducing their round-trip efficiency,[63] and lithium-ion batteries suffer capacity loss when cycled fully.[64] Hydrogen can be stored in high volumes at low cost in salt caverns (see chapter 4.4) and be used in combined heat and power and combined cycle plants using hydrogen turbines or reciprocating engines, replacing existing lower-efficiency turbines.

Further assessment is needed regarding the magnitude of seasonal storage needs in high renewable electricity systems in the UAE. Seasonal electricity demand in this region is aligned with renewable generation, since space cooling demand correlates with solar irradiation. The demand for long-term storage could be smaller than in Germany, where energy demand is higher in winter due to space heating. However, a massive scale-up of PV in the UAE might lead to significant curtailment volumes in the winter, potentially creating a business case for cheap electricity to be stored and sold in summer.

Hydrogen is well suited as a long-term electricity storage medium



5.3.3 Reducing the need for grid expansion

In most regions, the investment cost of electricity lines is typically 2-10 times greater than it is for gas pipelines.[65] It could be attractive to convert renewable electricity to hydrogen or methane and transport it through a pipeline rather than building an electricity line. The downside of this are the high conversion losses of hydrogen or methane production (see chapter 3.1).

As Figure 5-1 shows, using Power-to-Gas is only cheaper than electricity transmission if energy needs to be transported over longer distances (greater than approximately 3,500 km) and if electricity is cheap (less than 2 ct/kWh-3 ct/kWh). From this pure transmission cost perspective, Power-to-Gas would not be competitive in Germany, where offshore wind power needs to be transported around 600 km to load centres in southern Germany or in the UAE, with the Mohammed bin Rashid Al Maktoum Solar Park being located less than 100 km away from Dubai and the Noor Abu Dhabi solar park around 100 km away from Abu Dhabi.

There are cases where hydrogen transmission may still be the preferred option over electricity transmission:

- If the end use is hydrogen and not electricity, conversion losses will occur anyway and hydrogen transmission becomes cheaper due to lower upfront investment.
- For renewable energy trade between Germany and the UAE, hydrogen transmission would also be cheaper due to the long distance, provided that renewable electricity costs no more than 2 ct/kWh-3 ct/kWh (see Figure 5-1 and chapter 4.1).
- If there are special obstacles to electricity grid expansion. In Germany, high population density and extensive agriculture have led to difficulties with the construction of power lines. In the UAE, these issues are not as prevalent.

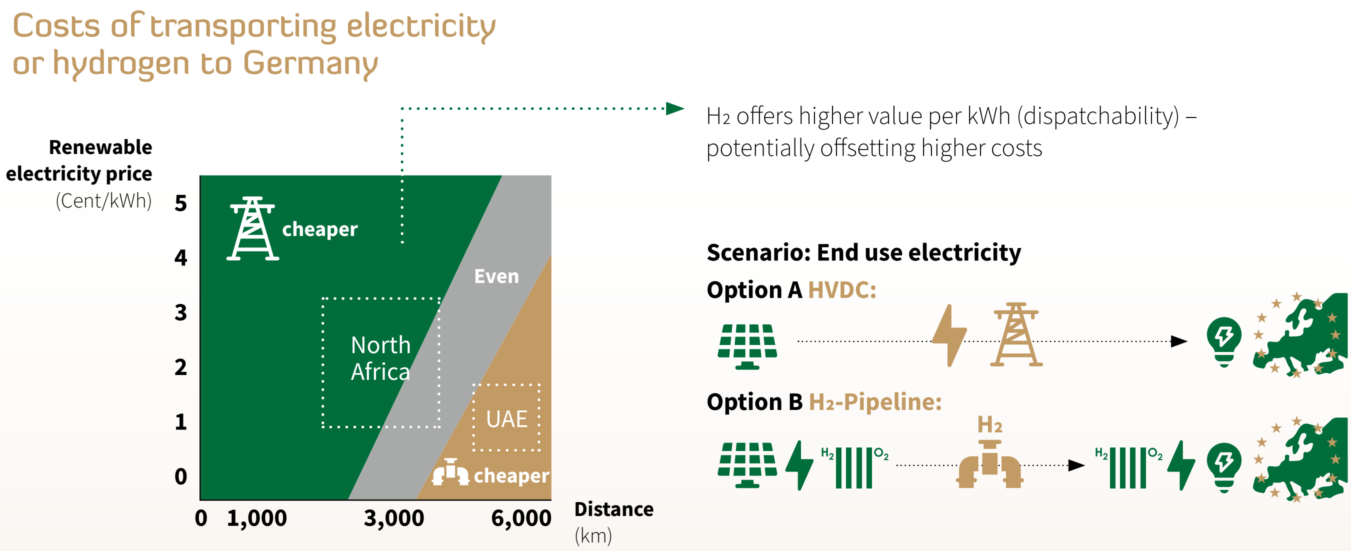


Figure 5-1: **Costs of transporting electricity or hydrogen to Germany in 2030 if the final consumption is electricity**
Source: Guidehouse (2020)

5.3.4 Space heating

Hydrogen and its derivatives can be used in space heating, such as with gas or oil boilers. In the UAE, this is less relevant due to little heating demand. In Germany, residential and commercial space and water heating accounts for 12.8% of total GHG emissions, out of which 9.5% relates to residential gas and oil boilers.[66]

Green hydrogen or synthetic methane in principle present an option to decarbonise heating while using existing infrastructure. Alternative decarbonisation options like electric heat pumps or district heating are much cheaper.[67] Green gas-based heating may be limited to hybrid systems where a heat pump is combined with a small gas boiler that uses green hydrogen or synthetic methane and is only operated on the coldest days in the year.[68]

5.4 Applications in the transport sector

The transport sector is a major contributor to total GHG emissions in both countries. The sector accounts for 15% (2016)[69] of the UAE's and 19% (2017)[70] of Germany's emissions. To decarbonise the sector, pure hydrogen or its derivatives can be used as a fuel. Different transport modes on the road, waterways, and in the air will rely on different fuels.

5.4.1 Hydrogen as a fuel

There are available models for fuel cell passenger and freight vehicles, including busses, but fuel cell electric vehicles (FCEVs)[71] do not play a significant role in any country to date. Other FCEVs such as ferries are in development.[72] Japan and China have set ambitious goals for the market uptake of FCEVs, which will likely increase model availability. In the UAE, Abu Dhabi Police and the Dubai Taxi corporation are currently testing the Toyota Mirai for use in their fleet, with Abu Dhabi Police aiming to convert its entire fleet of police vehicles to FCEVs by 2057.[73] Besides the self-prescribed goal of Abu Dhabi Police to convert its fleet to FCEVs, there are no political targets related to FCEVs and the attention to the technology has been limited in previous years. Germany is starting to use FCEV busses; in Hamburg, several FCEV busses are in operation.[74] In the UAE, a pilot project featuring FCEV busses fuelled by green hydrogen from the Siemens electrolysis plant at the Mohammed Bin Rashid Al Maktoum Solar Park is planned for the EXPO in Dubai.

Hydrogen's low energy density limits its possible applications in the transport sector. For airplanes, the tanks would have to be too large to fit enough fuel for long-distance air travel. Similarly, it would not be economical to fuel tankers with hydrogen, as too much storage space would be taken up by the voluminous hydrogen tanks. The energy efficiency of hydrogen as a fuel is higher than that of its derivatives, but significantly lower than direct electrification of transport (see Figure 5-2). Battery electric vehicles (EVs) should be used wherever possible. To use hydrogen as a fuel, new fuelling charging infrastructure is needed. The construction of decentralised fuelling infrastructure for road passenger and freight transport largely depends on political commitment, as private investors are unlikely to commit if the business case is not profitable.

Germany supports a hydrogen fuelling infrastructure[75] and has over 70 charging stations (2019).[76] For the UAE, Air Liquide, Al Futtaim, and Khalifa University argue that relatively few fuelling stations are needed due to the centralised population in Abu Dhabi, Dubai, and a few other cities.[77] The first public hydrogen fuelling station in the UAE was opened in Dubai Festival City in October 2017 by Al Futtaim and Air Liquide.[78] Further fuelling stations are planned in Masdar City in collaboration with ADNOC, Masdar, and Al Futtaim,[79] and on the EXPO 2020.

Hydrogen as a fuel could be a feasible option for long-distance passenger car travel, heavy duty road freight transport, and smaller boats such as ferries.

5.4.2 Hydrogen derivatives as a fuel

Green hydrogen derivatives including gasoline, diesel, kerosene, methanol, and ammonia are being considered to replace their fossil equivalents, especially in maritime and air transport. Large-scale production is still in the R&D phase, but there are pilot projects underway. Some hydrogen derivatives could replace their fossil equivalents directly, which means that hardly any new infrastructure would be needed. Using ammonia would require the development of new vehicles and additional infrastructure.

Once the technologies become commercially viable, the UAE could become an important off-taker. Dubai's Jebel Ali port is one of the world's most important (14.95 million TEU[80]/year).[81] Similarly, there are major airports like Dubai International Airport and Abu Dhabi International Airport and large airlines such as Etihad and Emirates.

The readiness to pay a premium for carbon-neutral fuel is already high for some airlines and will likely increase with more ambitious climate targets. The current readiness to pay is apparent in Emirates' biofuels project.[82] Lufthansa has committed to take off hydrogen-based synthetic kerosene that will be developed and produced as part of a research project KEROSyN100, funded by BMWi.[83]

There is a high degree of certainty that green hydrogen-based kerosene will be needed for ambitious decarbonisation, developing this now would be a no-regret move.

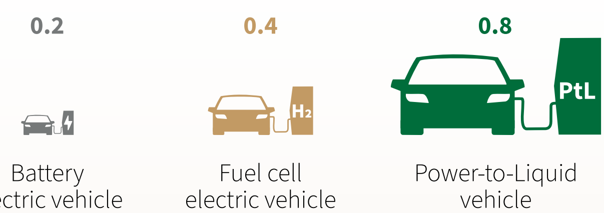


Figure 5-2: **Electricity needed for driving a passenger car 1km (kWh)**
Own calculation assuming 0.15 kWh/km for BEV

5.5 Hydrogen demand scenarios in Germany

Several studies have conducted integrated energy system modelling to assess how Germany can become carbon neutral and what role hydrogen and its derivatives can play. Figure 5-3 summarises the resulting synthetic fuel demand in Germany 2050 as modelled by BCG,[84] dena,[85] and ESYS.[86] This includes hydrogen and its derivatives. However, to safeguard achievement of ambitious climate targets, an early scale up of supply and demand technologies is necessary.

There are significant differences between the modelling results; dena estimates a synthetic fuel demand above 900 TWh in a 90 %–95 % GHG reduction scenario, while BCG and ESYS foresee well below 500 TWh. These differences are largely due to differing projections of whether hydrogen and its derivatives will be competitive against other decarbonisation technologies, such as CCS for steelmaking or direct electrification in the transport sector.

There are several common findings across the studies:

- Synthetic fuel demand is mainly driven by ambitious climate action. Figure 53 shows that synthetic fuel demand in 90 %–95 % GHG reduction scenarios is disproportionately higher than in 80%-85% scenarios. Hydrogen and its derivatives are one of the most expensive decarbonisation technologies. Most of it will be employed only on the last metres to become carbon neutral.
- Full decarbonisation of the German economy will require large volumes of carbon-neutral synthetic fuels.
- Domestic production would cover only up to approximately 200 TWh of demand, the rest needs to be imported.

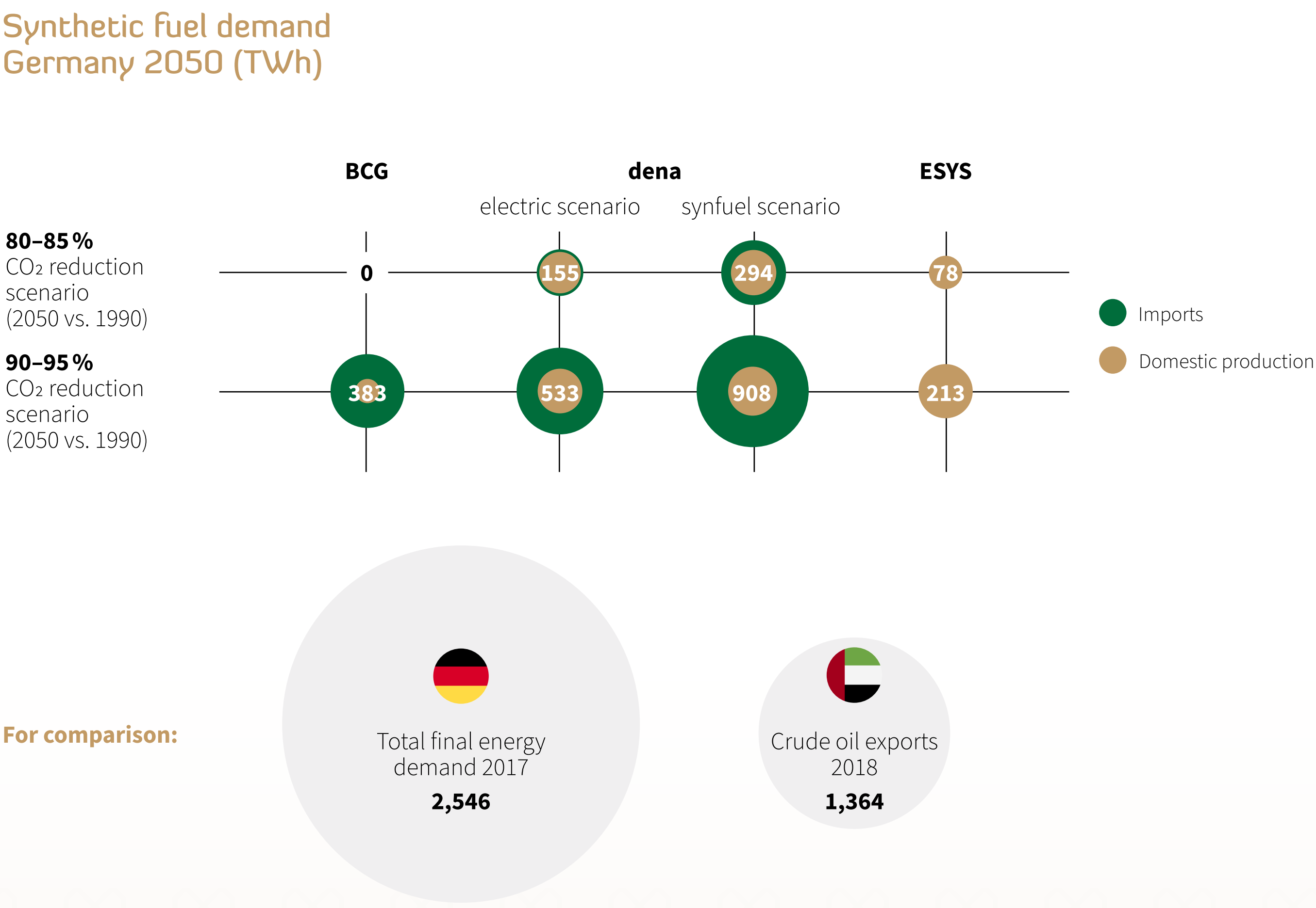


Figure 5-3: **Synthetic fuel demand in GHG reduction scenarios from three studies.**
Source: Guidehouse (2020), The Boston Consulting Group (2018), dena (2018), ESYS (2017), AG Energiebilanzen, OPEC

6

Potential for cooperation
between the UAE & Germany

Close cooperation between Germany and the UAE in all areas along the hydrogen value chain will be valuable to both countries. The Energy Partnership (see chapter 1) is an ideal platform to continue to deepen the cooperation on hydrogen.

The Energy Partnership is an ideal platform to continue to deepen the Emirati-German cooperation on hydrogen

There are many open questions around the production, applications, and trade of hydrogen, and the timeframe of these developments. There are several no-regret moves for the bilateral cooperation that can help accelerate the deployment of this technology. Based on the dialogue in the Energy Partnership and considering the findings of this study, some potential next steps are listed below.

Cooperation potential in production:

- Joint projects for energy carriers that are particularly promising to both countries to become early adopters (e.g. green hydrogen-based kerosene).
- Excursions to existing production sites in Germany and the UAE to provide mutual learning and an exchange of experiences.
- Technology cooperation (e.g. between German electrolyser manufacturers and Emirati large-scale renewables producers or oil & gas companies) to combine strengths and ensure that the hydrogen value chain adds to local value creation.
- Structured discussions on sustainability criteria to safeguard GHG reductions through hydrogen and ensure a predictable regulatory framework for plant operators.

Cooperation potential in hydrogen transport and trade:

- Simultaneous creation of demand, such as through quotas or auctions, to trigger the emergence of a market for hydrogen and its derivatives.
- Initial discussions on hydrogen market designed to assess potential direct purchase agreements, open market solutions, price setting, and more.
- Creating a common understanding on the role of GHG regulations (e.g. carbon taxes) in the formation of national and international hydrogen markets.
- Matching stakeholders from both countries to jointly fund and implement pilot projects on transport, such as the shipping of hydrogen derivatives or hydrogen pipelines.

Cooperation potential in end uses:

- Excursions to existing end use sites in Germany (refineries, seasonal storage projects, hydrogen refuelling stations, hydrogen in transport) and corresponding workshops to identify the most attractive application cases for each country.
- Technology cooperation (e.g. in the chemical or steel industry) to accelerate learning and share R&D costs.

7 Association & Company profiles

3 Association Profiles / 18 Company Profiles

Electrolyser Manufactoring

Power-to-X O & M

Storage & Distribution

End Use: Mobility

End Use: Industry

German Association for Concentrated Solar Power

German Association for Concentrated Solar Power (DCSP)

©DCSP – German Association for Concentrated Solarpower

The German Association for Concentrated Solar Power (DCSP) has been representing the corporate interests of the industry in Germany and international markets since 2013.

Concentrated Solar Power (CSP) can be used to generate green electricity, green heat and green hydrogen. The plants supply temperatures from 50° C to 500° C. The great advantage of concentrating solar thermal energy is the possibility of effective storage, permitting a high degree of coverage and a seasonally more balanced supply of heat. In combination with biomass or PV, CSP power plants can then continuously provide energy in the base load range similar to a conventional power plant. CSP is a globally proven reliable, cost-effective and affordable power plant technology.

Most of the CSP technology is developed and manufactured in Germany. Members of the DCSP cover the whole value chain: consulting and engineering companies, manufacturers of components, owners and operators of power plants as well as research institutions.

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Deutscher Wasserstoff- und Brennstoffzellen-Verband

German Hydrogen and Fuel-Cell Association (DWV)

The DWV is the umbrella organization of all those in Germany who are committed to the general use of hydrogen as an energy carrier in the economy. The mission of the DWV is to ensure that hydrogen is produced from renewable energy sources for a sustainable energy economy.

Since 1996 the DWV is focused on promoting the rapid market introduction of green hydrogen as an energy carrier and fuel cell technology. The aim of the association is to bring all aspects of a future supply infrastructure of hydrogen, its production and energetic use into a factual and perspective discussion and to actively participate in shaping the market development. As the national association representing the German hydrogen industry, the DWV also promotes the international trade of hydrogen and its downstream products.

One of the core competencies of the DWV is the development and implementation of concepts for secure, economical and emission-free mobility and energy supply, as well as strategies for sustainable and climate neutral industries.

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Working Group
Power-to-X
for Applications

VDMA Power-to-X for Applications

The VDMA Working Group "Power-to-X for Applications" is a cross-industry platform for exchange, information, communication, and cooperation in the Power-to-X (P2X) community. It involves all important stakeholders along the value chain, from the development of manufacturing processes through the production of synthetic fuels and raw materials using power-to-X technologies to the end customer. With its activities, the group promotes a holistic and technology-open approach to the transformation of energy systems and sensitizes the public to environmentally friendly energy consumption and mobility. Founded end of 2018 as the P2X platform of VDMA e.V., which is the largest network organization with more than 3,300 members, and an important voice for the mechanical engineering industry in Germany and Europe, the Power-to-X for Applications Working Group has grown very fast and today has already more than 120 members.

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AREVA H_2Gen
We make it happen

AREVA H2Gen GmbH

AREVA H2Gen is a technology supplier for Proton Exchange Membrane (PEM) electrolysis systems, who develops, produces, and distributes PEM electrolysis plants. With the PEM electrolysis system green hydrogen can be produced, which is used in industrial applications, markets of mobility or to store renewable energies. The applications are sold in the fields of electricity and gas management, neighborhood concepts, sector coupling, hydrogen mobility and filling stations. The CE certified systems range from a hydrogen production of 5 Nm^3/h up to 2.000 Nm^3/h. The systems are characterized by high dynamics and an overload capacity of up to 100 %.

The young company draws on the knowledge of more than 30 years of research and development in PEM technology, which is unique in Europe.

List of major projects

- Lighthouse project supported by the German Federal Ministry for Economic Affairs and Energy, Frequency Containment Reserve for stabilizing the grid; Germany
- Store energy in remote areas facing grid export limitation, using energy from wave, tidal and wind; UK
- Hydrogen refueling station for utility vehicles; France
- Hydrogen refueling station for passenger vehicles, coupled with PV; Germany

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Eupener Straße 165, 50933 Cologne, Germany
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AVL Schrick GmbH

AVL Schrick GmbH (AVL) has more than 400 employees in Germany and is an independent company for the development, simulation, and testing of all types of powertrain systems.

The AVL's solutions for the energy transition are: Concise description of global emission reduction strategies and global energy roadmaps, analysis of market trends, energy provider and portfolio strategies, identifying possible scenarios and impacts on the industry and identifying technologies that support the energy transition. AVL provides a complete, objective picture of all existing and potential global energy and fuel scenarios, creates confidence by defining the right future technology roadmap, and offers market-specific and independent recommendations for qualified and balanced solution packages at the intersection of energy and mobility.

List of major projects

- Hydrogen in Mobility, Strategy Consulting, UK
- Synthetic Fuel Production, Efficient Production Technologies, Europe
- Sustainable Energy, PEM Based Stationary Genset, Middle East
- Sustainable Energy, Co-Electrolysis and Methanation, Austria

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We create chemistry

BASF FZE

BASF creates chemistry for a sustainable future, while combining economic success with environmental protection and social responsibility. More than 117,000 employees in the BASF Group work on contributing to the success of customers in nearly all sectors and almost every country in the world. The portfolio is organized into six segments: Chemicals, Materials, Industrial Solutions, Surface Technologies, Nutrition & Care and Agricultural Solutions.

Major project

- Methane pyrolysis: A ground-breaking new way to produce hydrogen led by BASF

SPONSORED BY THE
Federal Ministry of Education and Research

As part of BASF's Carbon Management R&D program, it is working together with cooperation partners in a project funded by the Federal Ministry of Education and Research (BMBF) to develop a new process technology for producing clean hydrogen – methane pyrolysis, in which methane or natural gas is split directly into hydrogen and solid carbon. The process uses comparatively little energy and, if it is run using electricity from renewable resources, is even CO_2-free.

An initial reactor concept with a moving carbon bed has been tested at lab scale. Currently, BASF is building a 15 m high test facility at the Ludwigshafen site. The aim is to create a stable functioning test reactor. It is to be put into operation end of 2020. If it operates successfully, commercial methane pyrolysis could be pursued.

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Bilfinger SE

Bilfinger is a leading international industrial services provider. The Group enhances the efficiency of assets, ensures a high level of availability and reduces maintenance costs. The portfolio covers the entire value chain from consulting, engineering, manufacturing, assembly, maintenance and plant expansion to turnarounds and also includes environmental technologies and digital applications.

Bilfinger delivers products and services that allow its customers to benefit from hydrogen technology across the entire hydrogen value chain from production, storage and transportation to utilization. The service portfolio includes consulting and engineering, plant construction and EPC services, maintenance and technologies.

List of major projects

- Design of hydrogen production plants (North Sea Energy Program)
- Development of hydrogen high-pressure storage tanks (DLR)
- Various services for the construction of the pilot plant HyStock (Gasunie)
- Engineering and construction of hydrogen filling station (Air Liquide)

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Elia Grid International GmbH

Elia Grid International GmbH (EGI) is an international consulting company providing consultancy services in market development, asset management, power system operations and security, system and market operations, owner's engineering, and investment advisory to international clients in the power sector. It is a full subsidiary of the Elia Group, which is organised around two transmission system operators: Elia in Belgium and 50Hertz, one of four German transmission system operators. EGI benefits from its position as a subsidiary of two European System Operators and offers proven expertise and hands-on experience based on the best practices of its parent companies. The company also plays a catalysing role in the Elia Group by providing valuable international insights and innovative solutions to Elia and 50Hertz.

List of major projects

- National Grid, Assessment of the impact of the integration of 60 GW of RES, Saudi Arabia
- KACARE, Set Up of a Management Centre to Forecast and Coordinate RES Producer, Saudi Arabia
- Transco, Support the Operational Readiness for the Arrival of RES and Nuclear Production, UAE
- Review of Power Purchase Agreement in the Context of Electricity Market Evolution, Procurement Company, Saudi Arabia

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Enapter GmbH

Enapter designs and builds the AEM electrolyser, one of the most efficient green hydrogen generators. Enapter's electrolysers are standardised, scalable, and flexible. They run in over 30 countries across all sectors, striving to make electrolysers a commodity. Currently, the scale of production is to deliver low cost devices that will produce hydrogen for industrial and commercial purposes, energy storage, transport, or fuel for heating. Enapter's team also developed its software-defined Energy Management System (EMS). The EMS is a decentralised energy system controller. Enapter's approach is to build the EMS as an operating system for any energy system that offers core functionality, and can easily be built upon to accommodate individual needs via open collaboration tools.

List of major projects

- DNVGL, Power-to-Heat, The First Hydrogen Project for Residential Heating, The Netherlands
- ZeroAvia HyFlyer Project, Decarbonise Medium Range Passenger Aircrafts Using Hydrogen, UK
- [White label], Stand-Alone Hydrogen Energy Supply System Using Solar Energy and AEM Technology, Japan
- Southern Green Gas, Power-to-Gas, Australia

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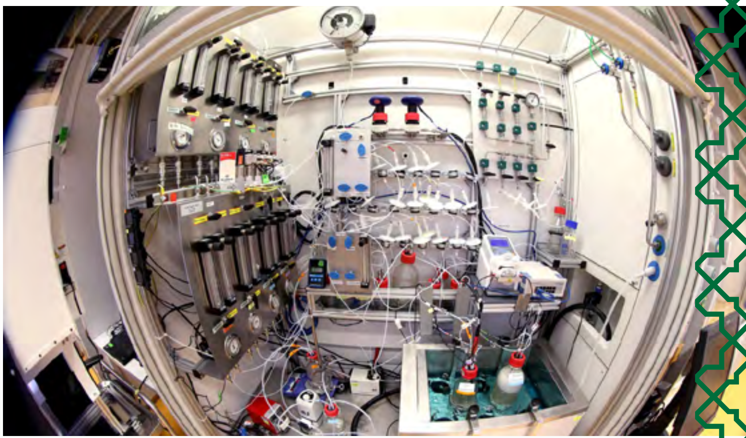
Evonik Industries AG



Evonik Industries AG, one of the world's leaders in specialty chemicals, developed a new type of an ion-conducting membrane intended to help green hydrogen production achieve a breakthrough by means of electrolysis. The new membranes consist of a resistant polymer with excellent performance indicators that are key to the effectiveness and efficiency of the electrolysis process in the production of green hydrogen. The advantages of electrolysis with ion-conducting membranes include lower investment costs, high current density, efficiency, and high flexibility.

Green hydrogen is of great relevance to the renewable energy industry in the Middle East where massive solar energy projects are being developed, such as Noor in Abu Dhabi, the world's largest solar project with a capacity of 1,177 million W through 3.2 million solar panels installed over 8 km².

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FEV Group GmbH

FEV is a leading independent international service provider for the transportation and energy industry, established in 1978 with a global staff of 6,700. The range of competencies includes advisory and consulting services, development and testing of innovative solutions up to series production and the production of prototypes and low-volume series products. FEV has over 20 years of experience in fuel cell systems and hydrogen combustion engines along the full development cycle. Within FEV Group, FEV Consulting is the strategic management consultancy, that combines top management consulting expertise with the technical capabilities and knowhow of the FEV Group. FEV Consulting works across the entire hydrogen economy, i.e. hydrogen-based business models, hydrogen production, transport and distribution, hydrogen powered applications for any transportation mode.

List of major projects

- Fuel cell validation from cell to system including fuel cell system endurance testing, development of a fuel cell range extender including vehicle integration and validation
- Development and testing of a commercial vehicle hydrogen combustion engine
- Analysis of value creation and macro-economic impact of fuel cell powertrains
- Market and technology study on hydrogen microgrids

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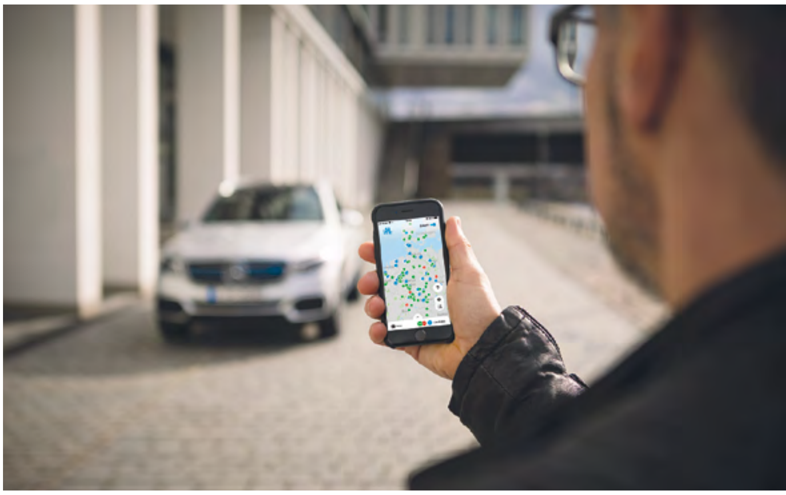

H2 MOBILITY Deutschland GmbH & Co KG

H2 MOBILITY Deutschland GmbH & Co KG, is responsible for establishing a nationwide hydrogen infrastructure to supply vehicles with fuel-cell drives in Germany. H2 MOBILITY is building a mobile future of rapid refuelling, long ranges, and clean and quiet mobility. There is no comparable entrepreneurial initiative in the world that sees the introduction of a zero-emissions fuel as a national duty and works towards it in this spirit. H2 Mobility is handling all of the operational tasks, including network planning, permitting, procurement, construction, and operation. Shareholders include Air Liquide, Daimler, Linde, OMV, Shell, and TOTAL. Associated partners include BMW, Honda, Hyundai, Toyota, and Volkswagen, Germany's National Organization for Hydrogen and Fuel Cell Technology (NOW GmbH).

Major Project

- 100, The first goal is to operate 100 hydrogen stations in seven metropolitan areas and along the connecting arterial roads and motorways, Germany

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H-TEC SYSTEMS GmbH

H-TEC SYSTEMS GmbH is an internationally active company in the field of renewable energy and hydrogen, with offices in Braak and Augsburg, Germany. Since the company was founded in 1997, H-TEC SYSTEMS has been successfully developing innovative products for the production and supply of green hydrogen and is actively driving the energy revolution.

Highly efficient electrolysers and stacks make H-TEC SYSTEMS a technology leader in PEM electrolysis, which also contributes to making the customer's value chain carbon neutral. Together with the investors GP JOULE and MAN Energy Solutions, the implementation and further development of innovative Power-to-Gas solutions are in progress.

©GP Joule

List of major projects

- Hydrogen Refueling Station Westre, Wind Energy into Green Hydrogen, Germany
- eFarm, Germany's Biggest Green Hydrogen Mobility Project, Germany
- H2 Project Haurup, Electrolyser with a Nominal Capacity of 1 MW, Germany

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Hydrogenious LOHC Technologies GmbH

Hydrogenious LOHC Technologies has developed a commercially available liquid organic hydrogen carrier (LOHC) technology for the safe handling of hydrogen. The innovative solution is based on a commercially available heat transfer oil. LOHC-technology is expected to become the backbone of a global renewable energy infrastructure.

Hydrogenious's technology is applied to efficiently store and flexibly distribute hydrogen from sources to use points in industry and mobility. The utilisation of the existing fuel infrastructure for the transportation of LOHC is a significant advantage.

List of major projects

- HySTOC, First European LOHC Hydrogen Refueling Station. Cost-effective transport and storage of hydrogen, Finland
- Hydrogen Refueling Station with Hydrogen LOHC underground Tanks, Hydrogen Supplied via LOHC technology, Germany
- Industrial Scale H_2 Storage Plant Based on LOHC technology, Germany
- IPCEI EU-Funded Projects: Green Hydrogen Import to Central Europe by LOHC Technology, Europe

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ILF Consulting Engineers GmbH

Hydrogen enables sector coupling and supports the energy transition from molecules to electrons. For decades ILF Consulting Engineers (ILF) has helped clients around the world successfully implement large energy infrastructure projects.

ILF Consulting Engineers has the competence and capability to consult with clients on concepts; execute different phases of design; assist during permitting, construction, and commissioning; and to manage projects to lead project implementation to success.

The company integrates all types of assets from wind, solar, or hybrid power, from water treatment and seawater desalination plants through water and power transmission systems to hydrogen production, and injection into gas networks, pipelines, and storages. ILF provides solutions to supply the industry and mobility sector with renewable energy from all over the world.

List of major projects

- Dii, Large Scale Hydrogen Production and Long-Distance Transportation, Middle East and North Africa
- The Red Sea Development Project, Energy Storage with Hydrogen Study, Kingdom of Saudi Arabia
- Element Eins Power-to-Gas, Gasunie / TenneT / Thyssengas, Germany
- Demo4Grid Green Hydrogen Production Plant, Austria

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Linde GmbH

Linde is a global leader in the production, processing, storage and distribution of hydrogen. It has the largest liquid hydrogen capacity and distribution system in the world. The company also operates the world's first high-purity hydrogen storage cavern coupled with an unrivalled pipeline network to reliably supply its customers. Linde is at the forefront in the transition to clean hydrogen and has installed over 180 hydrogen fueling stations and 80 hydrogen electrolysis plants worldwide. The company offers the latest electrolysis technology through its newly formed joint venture ITM Linde Electrolysis.

Main Projects/Clients

- Hydrogen liquefaction: Liquefaction plant with ongoing expansion project to double production capacity. Leuna, Germany
- Pre-combustion capture of CO_2: Capture of 600 tons per day of CO_2 and subsequent purification for further usage. Porvoo, Finland
- Hydrogen Refueling Station: next generation 100% renewable hydrogen refueling station for passenger cars. Fountain Valley, USA
- Upstream removal of CO_2 with pressure swing adsorption: 315 tons per day CO_2 are captured and purified for further usage. Leuna, Germany

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Mr. Martin Dworak – Linde Engineering Middle East LLC

Ludwig-Bölkow-Systemtechnik GmbH

Ludwig-Bölkow-Systemtechnik GmbH (LBST) is an expert consultant for sustainable energy and mobility. With expertise in bridging technologies, markets, and policy, LBST supports public and private international clients in strategy, feasibility, and market assessments. International blue-chip companies trust LBST's judgment. The competence offered is based on over 3 decades of continuous experience and an interdisciplinary team of leading experts. Hydrogen-related activities include techno-economic analyses, modelling, and feasibility studies of large-scale hydrogen generation and supply infrastructure, as well as detailed work on the associated regulatory and market environment. With its understanding of developments and technologies and truly independent advice, LBST help clients with sustainable decisions to secure their future.

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Main Projects/Clients

- Study on Introducing Hydrogen into the Energy Sector, Project Developer, Oman
- Feasibility Study for a 100 MW Power-to-Gas Project, Transmission System Operators, Europe
- Impact of International Climate Action Targets on Worldwide Hydrogen Demand, Gulf Cooperation Council Countries
- Hydrogen Market Study and Demand Outlook, Oil Producer, Gulf Cooperation Council Countries

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Siemens Energy

Siemens Energy is one of the world's leading energy technology companies. The company works with its customers and partners on energy systems for the future, thus supporting the transition to a more sustainable world. With its portfolio of products, solutions and services, Siemens Energy covers almost the entire energy value chain – from power generation and transmission to storage. The portfolio includes conventional and renewable energy technology, such as gas and steam turbines, hybrid power plants operated with hydrogen, and power generators and transformers, including storage and sector-coupling solutions. More than 50 percent of the portfolio has already been decarbonized.

List of major projects

- Middle East and North Africa's First Solar-Powered Green Hydrogen Project in Partnership with Dubai Electricity & Water Authority and EXPO2020, United Arab Emirates
- World's Largest PEM Electrolysis Facility at Energiepark Mainz, Germany
- First Power-to-Gas Plant with Windgas Haßfurt, Germany
- European Flagship Project for Generation and Use of Green Hydrogen with H2Future, Austria

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thyssenkrupp Industrial Solutions AG

thyssenkrupp Industrial Solutions offers a unique set of solutions for synthesis of green chemicals. It offers alkaline water electrolysis producing green hydrogen with high efficiency. With decades of experience in industrial application, thyssenkrupp's alkaline water electrolysis was thoroughly designed and tested. The standardised modules easily enable large installations needed for industrial application. With industrial-scale electrolysis, thyssenkrupp has a track record and a unique portfolio of downstream processes: green ammonia, methanol, synthetic natural gas, fertilisers, and more. thyssenkrupp can offer a full range of Power-to-X technologies and complete project execution from a single source, enabling green value chains for decarbonising our society.

List of major projects

- The Carbon2Chem project includes a water electrolysis plant that produces hydrogen which is recombined with steel mill off-gases to green ammonia and green methanol.
- The STORE&GO demonstrates how green methane produced by Power-to-Gas technology provides a keystone for cross-sector energy.
- As a global technology and engineering, procurement, and construction partner, it has realised more than 2,500 chemical plants worldwide.

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VINCI Energies

In a world undergoing constant change, VINCI Energies focuses on connections, performance, energy efficiency and data to fast-track the rollout of new technologies and support two major changes: the digital transformation and the energy transition.

With their strong regional roots VINCI Energies' business units take care of safety and efficiency of energy, transport and communication infrastructure, factories, buildings and information systems. Operating in 53 countries worldwide, our 1,800 business units intervene in infrastructure, industry, Building Solutions and information and communications technology (ICT).

They are organised around international brands – Omexom, Actemium, VINCI Facilities and Axians – in addition to brands with a more regional identity.

List of major projects

- ONTRAS Gastransport GmbH (hydrogen plant of the company ENERTRAG in Prenzlau / H_2 feeding facility by ONTRAS)
- Métropole Rouen Normandie (a public body for intermunicipal coorperation in France), smart mobility project www.theagilityeffect.com/en/article/rouen-paves-the-way-for-the-refuelling-station-of-the-future/
- GRTgaz experimental site to trial its Power-to-Gas process www.theagilityeffect.com/en/article/jupiter-1000-power-to-gas-put-to-the-test/

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Wenger Engineering GmbH

Since 2007, Wenger Engineering GmbH has been a globally renowned simulation and development partner for leading companies in hydrogen technology such as Daimler, Toyota, Honda, Linde, and more. Wenger Engineering is the right partner for developing and operating filling stations, hydrogen storage tanks, or power-to-gas systems.

Wenger Engineering has developed simulation models for almost all components and subsystems. These are used in development projects for customers to find concepts that minimise investment and operating costs by maximising reliability.

The best-known model is its refuelling simulation, with which Wenger Engineering have made all simulations for the globally valid standard SAE J2601.

List of major projects

- Hydrogen Storage at Different Pressures and in Solids, Japan
- Hydrogen Refuelling Station Development, US, Germany, France
- Engineering and Optimisation of Power-to-X Projects, Germany
- Worldwide Standard for Hydrogen Filling Stations called SAE J2601, US

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List of Sources

1 Including H2 produced as by-product. Source: IEA (2019)

2 E.g. Hydrogen to Magnum (H2M) project: https://group.vattenfall.com/press-and-media/news--press-releases/newsroom/2019/hydrogen-an-important-step-towards-independence-from-fossil-fuels

3 IRENA (2018)

4 It should be noted that research is underway into powering a portion of the chlor-alkali chlorine production process from renewable energy. For example, see Chinello et al. (2017)

5 E.g. in Mainz, Germany (https://www.energiepark-mainz.de/en/) Prenzlau, Germany (https://ec.europa.eu/regional_policy/en/projects/germany/the-first-hybrid-electricity-fuel-heat-power-plant-with-hydrogen-storage-in-the-world) and Dubai, UAE (https://www.pv-magazine.com/2019/02/04/dewa-begins-work-on-hydrogen-facility-at-rashid-al-maktoum-park/ – operations expected to commence soon)

6 E.g. in Hamburg, Germany (https://www.hannovermesse.de/en/news/news-articles/hamburg-to-build-worlds-largest-hydrogen-electrolysis-plant)

7 E.g. Falkenhagen (www.uniper.energy/methanation-plant-falkenhagen-opens-important-step-successful-energy-transition)

8 E.g. by Audi in Dresden (https://www.audi-mediacenter.com/en/press-releases/fuel-of-the-future-research-facility-in-dresden-produces-first-batch-of-audi-e-diesel-352)

9 Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018)

10 Own calculation based on 800 $/kW Capex, 15 year lifetime, 6% WACC, 40 $/kW fixed Opex, 30 $/MWh electricity price

11 IEA (2019): The Future of Hydrogen. Available online: https://www.iea.org/publications/reports/thefutureofhydrogen/

12 IRENA (2019)

13 Presentation by Siemens at a Workshop if the Energy Partnership in Abu Dhabi on Feb. 20, 2020

14 Hydrogen Europe (2020); IRENA (2018)

15 IRENA (2018)

16 Guidehouse (2020)

17 BMWi (2020)

18 AG Energiebilanzen (2020)

19 BMWi (2020)

20 Agentur für Erneuerbare Energien (2019)

21 The Boston Consulting Group (2018)

22 OEC (2020)

23 Expert presentation at a Workshop of the Energy Partnership in Abu Dhabi on Feb. 20, 2020

24 Ibid.

25 Guidehouse (2019)

26 Expert presentation at a Workshop if the Energy Partnership in Abu Dhabi on Feb. 20, 2020

27 Reddi et al. (2016). The amount can be reduced by utilizing special measures (e.g. boil-off capture).

28 IEA (2019)

29 Chi Kong Chyong et al. (2010)

30 PPIAF, World Bank (2013)

31 Note that this does not include investments in vessels and in liquefaction facilities at the exporter.

32 King & Spalding (2018)

33 Kawasaki (2019)

34 Directive 2009/119/EG

35 Hydrogen Europe (2020)

36 Aleksandra Mikołajczak et al. (2019)

37 cH2ange (2018)

38 T. Watanabe (2010). Note that the low estimate was for a 5,700 tonne system, whereas the high end of the range was for storage of 215 tonne.

39 World Steel Association (2018)

40 World Steel Association (2019)

41 Agora Energiewende und Wuppertal Institut (2019)

42 The Boston Consulting Group (2018)

43 Global CCS Institute (2017)

44 Institute of Energy Economics, Japan (2015)

45 Agora Energiewende und Wuppertal Institut (2019)

46 Directive (EU) 2018/2001, Article 25 (1) a)

47 Agora Energiewende und Wuppertal Institut (2019)

48 ThyssenKrupp (2020)

49 McKinsey & Company (2018)

50 Energy Transitions Commission (2018)

51 U.S. Geological Survey (2013)

52 BP (2019)

53 World Bank (2020)

54 Dechema (2017)

55 Eurostat (2020)

56 Gulf Petrochemicals & Chemicals Association (2016)

57 Agora Energiewende und Wuppertal Institut (2019)

58 The Boston Consulting Group (2018)

59 Ammonia Energy Association (2020)

60 Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018)

61 E.g. at the Mohammed Bin Rashid Al Maktoum Solar Park in the UAE (under construction) or Shagaya CSP in Kuwait

62 California Hydrogen Business Council (2015); IEA (2019)

63 GCell (2020)

64 Energy Futures Initiative (2019)

65 Saadi et. al. (2018)

66 The Boston Consulting Group (2018)

67 Ibid.

68 Guidehouse (2019)

69 Environment Agency Abu Dhabi (2019)

70 BMU (2019)

71 Fuel cell electric vehicles (FCV), which produce electricity from hydrogen with water as the byproduct.

72 Green Shipping News (2020)

73 Air Liquide, Al-Futtaim motors & Khalifa University (2018)

74 NDR (2020)

75 NOW (2020)

76 H2 (2019)

77 Air Liquide, Al-Futtaim motors & Khalifa University (2018)

78 Gulf News (2017)

79 The National (2019)

80 Twenty-Foot Equivalent Unit (TEU) is a unit of cargo capacity for shipping

81 World Shipping Council (2019)

82 Gulf News (2019)

83 Business Insider (2019)

84 The Boston Consulting Group (2018)

85 Deutsche Energie-Agentur (2018)

86 ESYS (2017)

87 Euractiv (2020)

88 Germany's greenhouse gas intensity of the grid mix is 474 gCO_2/kWh (2017), in the UAE it is 600 gCO_2/kWh (2011).

89 UAE Ministry of Environment and Water (2015)

90 CertifHy (2019)

91 This study focuses only on climate sustainability. Social and economic sustainability are outside the scope.

92 Workshop of the Energy Partnership in Abu Dhabi on Feb. 20, 2020

93 Directive (EU) 2018/2001

94 World Resources Institute (2019)

95 Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018)

96 E.g., Kuang et al., (2019))

97 This would be relevant e.g. in the European Union, where double-counting for both the European Emissions Trading System and the end-use related targets would have to be avoided.

98 UK Department for Business, Energy and Industrial Strategy (2019)

99 IEAGHG (2017)

100 IEA (2019)

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