SERIES ON
ENERGY SYSTEMS OF THE FUTURE

Analysis March 2024

Options for importing green hydrogen into Germany by 2030:

Transportation routes, country assessments and implementation requirements

Frithjof Staiß (Chair) | Jörg Adolf | Florian Ausfelder | Christoph Erdmann | Manfred Fischedick| Christopher Hebling | Thomas Jordan | Gernot Klepper | Thorsten Müller | Regina Palkovits | Witold-Roger Poganietz | Wolf-Peter Schill | Maike Schmidt | Cyril Stephanos | Philipp Stöcker | Ulrich Wagner | Kirsten Westphal | Sven Wurbs

"Energy Systems of the Future" is a project of:

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Union of the German Academies of Sciences and Humanities | www.akademienunion.de

Impressum

Authors

Prof. Dr. Frithjof Staiß
(Chair)
Center for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW)

Dr. Jörg Adolf
Shell Deutschland GmbH

Dr. Florian Ausfelder
Society for Chemical Engineering and Biotechnology

Dr. Christoph Erdmann
MESSER GROUP GmbH

Prof. Dr.-Ing. Manfred Fischedick
Wuppertal Institute

Prof. Dr. Christopher Hebling
Fraunhofer Institute for Solar Energy Systems (ISE)

Dr. Thomas Jordan
Karlsruhe Institute of Technology (KIT) / Institute for Thermal Energy Technology and Safety (ITES)

Prof. Dr. Gernot Klepper
Institute for the World Economy (IfW)

Dr. Thorsten Müller
Foundation for Environmental Energy Law

Prof. Dr. Regina Palkovits
RWTH Aachen University – Institute for Technical and Macromolecular Chemistry

Dr. Witold-Roger Poganietz
Karlsruhe Institute of Technology (KIT)

Dr. Wolf-Peter Schill
German Institute for Economic Research (DIW Berlin)

Maike Schmidt
Center for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW)

Dr. Cyril Stephanos
ESYS Project Office | acatech

Philipp Stöcker
RWTH Aachen University – Institute for Power Electronics and Electrical Drives

Prof. Dr.-Ing. Ulrich Wagner
Technical University of Munich (TUM)

Dr. Kirsten Westphal
H2Global Foundation

Sven Wurbs
ESYS Project Office | acatech

Publisher of the series

acatech – National Academy of Science and Engineering (lead institution)
Munich Office: Karolinenplatz 4, 80333 Munich, Germany | www.acatech.de

German National Academy of Sciences Leopoldina
Jägerberg 1, 06108 Halle (Saale) | www.leopoldina.org

Union of the German Academies of Sciences and Humanities
Geschwister-Scholl-Straße 2, 55131 Mainz, Germany | www.akademienunion.de

Recommended citation:

Staiß, F. et al.: "*Options for importing green hydrogen into Germany by 2030: Transportation routes, country assessments and implementation requirements*", Series on "Energy Systems of the Future" (ESYS), 2024, ISBN: 978-3-9820053-6-2.

Scientific coordination

Maike Schmidt
ZSW

Dr. Cyril Stephanos
ESYS Project Office | acatech

Philipp Stöcker
RWTH Aachen University

Sven Wurbs
ESYS Project Office | acatech

Produktionskoordination und Satz

Annika Seiler, ESYS Project Office | acatech

ISBN: 978-3-9820053-6-2 | **DOI:** https://doi.org/10.48669/esys_2024-4

Bibliographic information: German National Library

The German National Library has recorded this publication in the German National Bibliography; detailed bibliographic data can be retrieved from the internet http://dnb.d-nb.de.

Academies' Project "Energy Systems of the Future" (ESYS)

The academy project „Energy Systems of the Future" develops position papers and analyses on shaping the energy transition. Position papers contain policy options for the transformation of the energy system and are adopted by the Board of Trustees of the academy project after external review. Analyses are reports on the results of working groups. Responsibility for the content of analyses lies with the authors. If an analysis contains assessments, these reflect the personal opinions of the authors.

Leopoldina
Nationale Akademie der Wissenschaften

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DEUTSCHE AKADEMIE DER TECHNIKWISSENSCHAFTEN

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DER DEUTSCHEN AKADEMIEN DER WISSENSCHAFTEN

Options for importing green hydrogen into Germany by 2030:

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Series on “Energy Systems of the Future” (ESYS)

Foreword

There is now no question today that green hydrogen is an important stepping stone on the pathway to achieving climate targets. Its future in Germany and Europe depends largely on the development of the renewable energy required to generate it. The more renewable energy is produced in Germany, the more potential there will be to generate green hydrogen domestically. Yet it is abundantly clear that as things stand we will need to continue importing energy from abroad. That includes hydrogen and its synthesis products as a priority. It is impossible to state with any degree of confidence how much hydrogen we will need to be importing by 2030. What we can say for certain, however, is that Germany and Europe need to exercise a proactive influence on the global markets as they emerge.

Now is the time to be laying the technological foundations and creating the economic and regulatory frameworks required to set up the international infrastructure for transporting hydrogen. And it is essential that we apply lessons from the past and present at this stage too. Russia's war of aggression in Ukraine and the resulting geopolitical upheavals leave no doubt that strategic cooperations and widespread sources are critical in protecting our planet, securing the energy supply and maintaining affordable energy prices.

A working group representing the "Energy Systems of the Future" (ESYS) Academies' Project explores in this analysis paper ("Options for importing green hydrogen into Germany by 2030") the ways in which green hydrogen and its synthesis products could be imported into Germany. The experts use quantitative and qualitative criteria to assess the available options for transportation. The analysis includes, among other things, the transparent presentation of production and transportation costs, environmental aspects and implementation timescales for each of the import solutions for a raw material and energy use as per the information available in 2021.

Individual country assessments are also provided as examples for selected distances and regional framework conditions. A material volume that accompanies the analysis paperprovides anyone who is interested with a closer look at the pool of data and calculation methods used. The working group hopes its analysis paper will support decision-makers by offering a differentiated, in-depth consideration of the various import options available for the purpose of building the Hydrogen Economy 2030.

I would like to take this opportunity to thank all of the members of the working group, the ESYS Project Office and everyone else who has been involved in this project. Extra special thanks go to the members of the core team: Maike Schmidt, Cyril Stephanos, Philipp Stöcker and Sven Wurbs. I hope you all find the analysis paper to be an interesting read.

Prof. Dr. Frithjof Staiß
Chair of ESYS-Working Group
"Hydrogen Economy 2030"

Contents

Abbreviations and units

€	Euro
BDI	Federation of German Industries
BMWi	Federal Ministry of Economics and Technology
CCS	carbon (dioxide) capture and storage
CCU	carbon (dioxide) capture and utilisation
CfD	contracts for difference
CO_2	carbon dioxide
CO_{2eq}	carbon dioxide equivalent (measure used to compare the emissions from greenhouse gases)
DAC	direct air capture (process of capturing carbon dioxide directly from the ambient air)
DE	Germany
RE	renewable energy
EEG	German Renewable Energy Sources Act
E-fuel	electrofuel (= synthetic fuels)
ENTSOE	European Network of Transmission System Operators for Electricity
EU	European Union
EU ETS	European Union Emission Trading System
Fraunhofer ISE	Fraunhofer Institute for Solar Energy Systems
FTS	Fischer-Tropsch synthesis
H_2	hydrogen
HINT.CO	Hydrogen Intermediary Network Company (non-governmental intermediary/subsidiary of not-for-profit H2Global Foundation)
IEA	International Energy Agency
IFO 380	heavy fuel oil
IRENA	International Renewable Energy Agency
kg	kilogram
km	kilometre
kWh	kilowatt hour
HGV	heavy goods vehicle
LNG	liquefied natural gas
LOHC	liquid organic hydrogen carrier
MIDAL	German natural gas pipeline (Central Germany Pipeline Link)
MJ	megajoule
N_2	nitrogen
NH_3	ammonia

OPAL	German natural gas pipeline (Baltic Sea Pipeline Link)
PtL	power to liquid (= electricity-based liquid fuel)
PtX	power to x (= conversion of electricity into chemical energy or heat)
PV	photovoltaics
RED	Renewable Energy Directive (EU)
RFNBO	renewable fuels of non-biological origins (= liquid or gaseous transport fuels)
SDG	Sustainable Development Goals (UN)
t	tonne (1000 kg)
TWh	terawatt hour
TWh/year	terawatt hours per year
UN	United Nations
WEDAL	German natural gas pipeline (West Germany Pipeline Link)
WTO	World Trade Organization

Summary

Whether or not Germany can be carbon-neutral by 2045 will also depend on whether hydrogen can be successfully utilised. The ramp-up of a **green hydrogen economy** which includes **a substantial, industrial-scale supply of hydrogen by 2030** is an **ambitious goal.** The strong rise in the demand for green hydrogen and its synthesis products by industry (e.g. steel, chemical and glass industries), transport (shipping, heavy goods transport and aviation in particular) as well as the energy industry (e.g. in power plants and as a storage medium) expected between now and 2030 can only be met if the market ramp-up is successful.

This analysis focuses on how hydrogen and its downstream synthesis products can be imported by Germany. It follows a **terminal-to-terminal approach** which analyses the **transport options and routes** – from the export terminal in the country of origin to the provision of the products at the import terminal in Germany. The way in which the hydrogen is produced is not relevant in this context. Nevertheless, the working group "Hydrogen Economy 2030" has decided to **focus** on **green hydrogen**[1] in order to stress its relevance for the transformation of the energy system and the attainment of climate neutrality.

According to the scenarios for climate neutrality in 2045, the **domestic demand** for hydrogen and its synthesis products is estimated to be between 45 and 100 terawatt hours by 2030. This demand is expected to increase sharply by 2045, reaching 400 to 700 terawatt hours in most scenarios.[2] Part of this volume will probably be produced in Germany, with additional substantial imports from other countries within – and probably also outside of – the EU. This analysis shows that the volume of **hydrogen imports expected to be required** by 2030 **can be met in principle**, **provided that** effective action is taken **swiftly to lay the foundations** in the form of infrastructure, regulatory and business frameworks.

1 In the definition used here, green hydrogen means hydrogen generated through electrolysis, i.e. using electricity to split water into hydrogen and oxygen. To ensure that the production chain is climate-neutral, the electricity used for the process must come from renewable sources exclusively.

2 BMWi 2020b, BDI 2021, dena 2021, Ariadne 2021a and Prognos/Institute for Applied Ecology/Wuppertal Institute 2021

Transport options available by 2030

This analysis looks at the **efficiency of the various transport chains** for hydrogen and its synthesis products, and at the **costs** incurred for imports into Germany at the border (quantitative evaluation). The various transport options are also assessed qualitatively, i.e. regarding the time needed for implementation, compatibility with the existing energy system or **environmental impact**.

The results show that **none of the transport options** for imports to Germany are **clearly superior** to others. Each option has its own **strengths and weaknesses**, as well as **different times and requirements for implementation**. Ultimately, the best option needs to be determined on a case-by-case basis, taking into consideration the specific application. There are, however, certain transport options that are more suitable for a fast transition into the green hydrogen economy on the basis of time, efficiency and costs. Regarding this we have to make a distinction between use as a **material** and use as an **energy source**, and between the use of pure hydrogen and the use as a synthesis product.

Figure 1 gives an overview of the transport options that were analysed. The faster the implementation of a particular option is, the further on the left it is shown, and the more expensive the energy carrier or raw material is compared with fossil-based variants,[3] the further up in the chart it is. However, costs and implementation time are not the only relevant criteria. In addition to the advantages and disadvantages of the options shown here, a key consideration is the extent to which today's fossil energy carriers can be replaced by direct electrification – which is generally more efficient – in certain areas of application or whether only synthetic hydrogen products are eligible for the climate-neutral switch in industry, the energy sector and transport.

Fast transition possible by importing ammonia and repurposing existing pipelines

A start could be made on **importing green ammonia as a raw material by ship right away** – to serve the chemical and fertiliser industries predominantly. With the entire production and transport chain having already been developed on an industrial scale, it would be possible to implement this option within around two years provided that enough green hydrogen were available. In this case, renewable ammonia (ammonia made with green hydrogen) could remove the need to import standard ammonia made with fossil fuel or replace some of the standard ammonia produced domestically. Based on the calculations, it would also be competitive in terms of costs in 2030.[4]

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3 In terms of costs, please note that the basis of comparison for the calculations is 2021, so that the risen energy costs of 2022 have not yet been included.

4 With production costs of under €3 per kilogram of hydrogen and with CO_2 at a price of around €100 per tonne for ammonia made with fossil fuel.

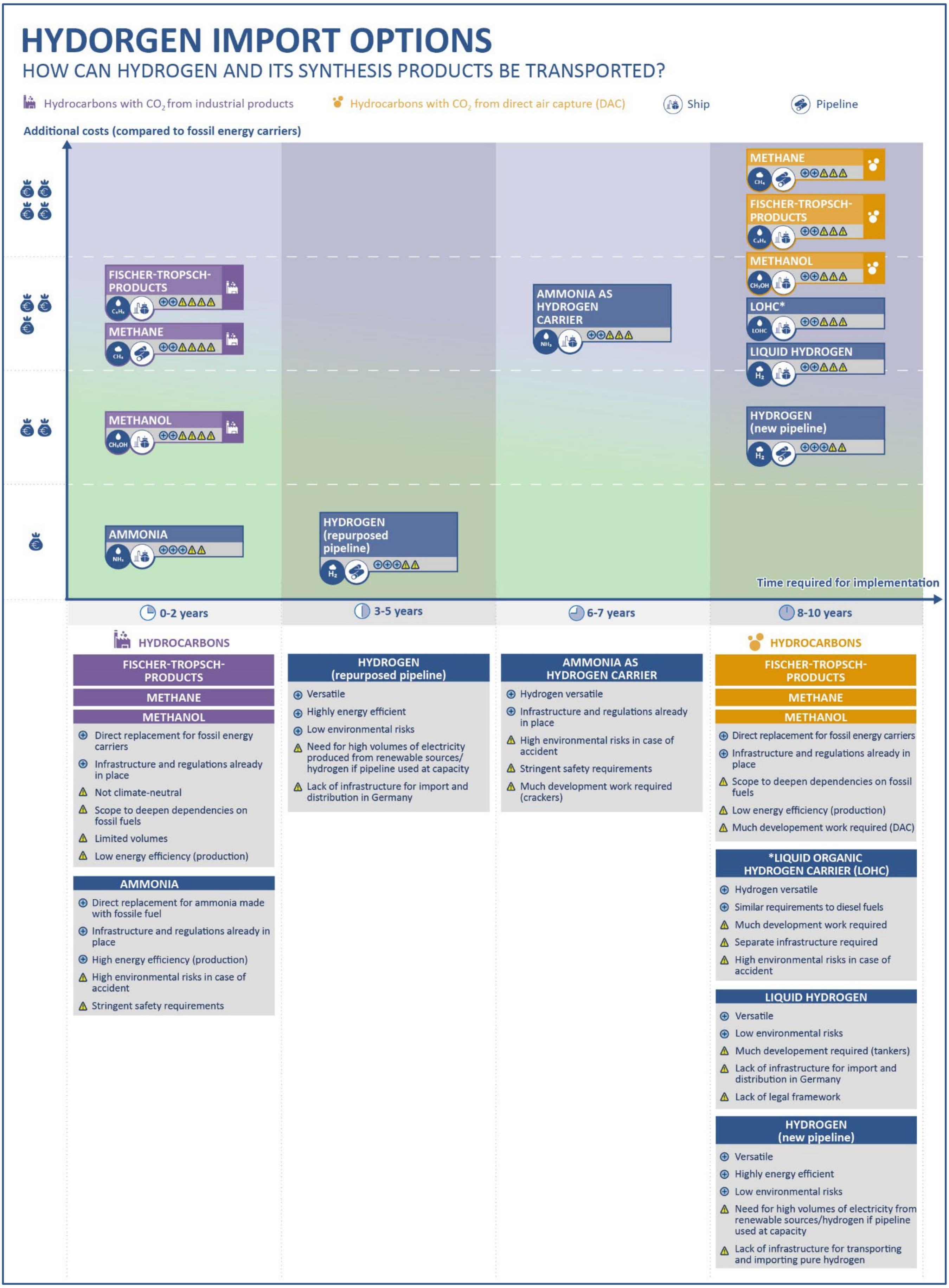


Figure 1: Hydrogen import options (source: Energy Systems of the Future, ESYS; illustration by Ellery Studio).

If the volumes of ammonia currently being imported into Germany were to be increased significantly (so it could go on to be used as a hydrogen carrier too, for example), the existing infrastructure for imports would need to be scaled up accordingly. This does not appear to be a feasible target to have achieved fully by 2030.

The option of **importing pure hydrogen** could be implemented in a timely manner if existing **natural gas pipelines** were **repurposed for transporting hydrogen** in gas form. With efficient planning and swift action alongside the expansion of the capacity required to generate electricity from renewable energy sources in the country of origin, significant volumes of hydrogen could be transported to Germany within around three to five years. Conversely, approximately eight to ten years would have to be allowed for the construction of a hydrogen pipeline from scratch on a route that does not yet exist.

If large pipelines were to be used, transporting pure hydrogen over distances of up to 4,000 kilometres is the most cost-effective of all the options explored. Moreover, that option also involves the most effective transport chain of all those considered. In addition, pure hydrogen is versatile in its usage as a material and energy source. The challenge here, however, is ensuring that such a huge and cost-effective hydrogen pipeline could be used to **capacity**. After all, the production of the required volume of hydrogen relies on sufficient capacity for electrolysis and a large supply of electricity generated from renewable sources. For a pipeline with a diameter of around 1,000 millimetres and the capacity to transport 6,000 to 7,000 tonnes of hydrogen every day (approximately 50 terawatt hours of hydrogen per year) that is used at around 60% of its capacity, around 85 terawatt hours of electricity would need to be made available in the exporting country. That equates to a combined wind power and photovoltaic system output of around 35 gigawatts.[5]

Synthetic methanol and products of Fischer-Tropsch synthesis available quickly in small volumes

Another option for a fast transition is presented by **importing green methanol and the products of Fischer-Tropsch synthesis**, which could all go on to be used materially. The CO_2 required for the synthesis would have to come from industrial point sources, which will not be avoidable in the medium term at least. Process emissions from cement production could be used, for example, but furnaces using fossil fuels would not count. With the infrastructure for transporting the materials already in place and with relatively little time required to modify existing synthesis systems, both options could be implemented within the space of two years or so.

5 An average of 2,500 full-load hours were assumed for the systems along with a utilisation of around 60% of the full capacity for the pipeline to account for a volatile feed-in. If the pipeline were used at full capacity, the costs would increase because storage facilities would then also be required for the renewable energy in the exporting country (cf. Section 4).

Renewable methanol could provide a direct replacement for methanol produced from fossil fuels, which is being used as a raw material in the chemical industry and elsewhere. With CO_2 priced at around €200 per tonne (database, 2021), this option would be economically competitive with standard methanol (produced from natural gas) before 2030.[6] Renewable Fischer-Tropsch products could also replace energy carriers that are currently derived from crude oil, such as diesel or kerosene. They are, however, likely to remain much more expensive than their counterparts produced from fossil fuels – even in the long term.[7]

Other transport options only available after 2030

If climate neutrality is to be achieved, the production of **synthetic hydrocarbons** (methane, methanol, Fischer-Tropsch products) needs to be gradually transitioned from the CO_2 sources that cannot be avoided for now to **sustainable CO_2 sources** or closed carbon cycles. One option that could be relied on here is direct air capture (DAC). However, it is expected that the costs associated with extracting the required volumes of CO_2 through DAC will still not be competitive by 2030.

Transporting **liquid hydrogen by ship** is another valid option beyond 2030. Importing hydrogen in this way makes most economic sense when the distance to be covered exceeds 4,000 kilometres because the major benefit of transportation by ship is that the distance has very little impact on the overall costs associated with hydrogen imports. The problem here is that the liquid hydrogen tankers required to make this a feasible transport option are still being developed. It is impossible to predict at this stage how long it will be before fleets of ships with the required capacity will be available for the commercial transportation of liquid hydrogen. It is also true that the regulatory framework conditions for importing liquid hydrogen by ship also need to be drawn up.

Hydrogen could also be transported using **carriers** like **LOHCs or ammonia**, which could then be dehydrogenated once they had arrived in Germany. From a cost perspective alone, this alternative is not as favourable as transportation in liquid hydrogen tankers. The fact that both technologies still also need considerable development and scaling draws out the timescale.

6 Cf. Section 4.
7 Cf. Section 4.

Import routes Examples of exporting countries and transport options		Energy efficiency of the transport chain	Costs of the imported product in Germany	Costs of the fossil fuel alternative in Germany per kWh*
Spain				
H_2	Gaseous hydrogen by pipeline	63%	€0.07–0.13	€0.08–0.11 Hydrogen
Ukraine				
H_2	Gaseous hydrogen by pipeline	64%	€0.065–0.125	€0.08–0.11 Hydrogen
Morocco				
LH_2	Liquid hydrogen by ship	51%	€0.095–0.155	€0.08–0.11 Hydrogen
NH_3	Ammonia by ship	49–59%	€0.09–0.16	€0.11–0.135 Ammonia
Saudi Arabia				
C_xH_x	Products of Fischer-Tropsch synthesis by ship	37%	€0.125–0.20	€0.06–0.085 Crude oil
CH_3OH	Methanol by ship	41%	€0.105–0.17	€0.085–0.11 Methanol
South Africa				
LOHC	Liquid organic hydrogen carrier (LOHC) by ship	43–57%	€0.145–0.205	€0.08–0.11 Hydrogen
C_xH_x	Products of Fischer-Tropsch synthesis by ship	37%	€0.125–0.20	€0.06–0.085 Crude oil
Brazil				
CH_3OH	Methanol by ship	41%	€0.105–0.17	€0.085–0.11 Methanol

Figure 2: Overview of the import routes considered by way of example for green hydrogen and/or its synthesis products, including data on the efficiency of the transport chain (with efficiency measures included in some cases), the price range for imports into Germany, and the costs of comparable fossil fuel alternatives in Germany (at a CO_2 cost of €100–200/tonne of CO_2). Cf. Section 7 for further details (source: authors' own calculations).

Examples of transport routes and exporting countries

The working group investigated six exporting countries as representative examples of different regions. Figure 2 presents the transport routes covered and reveals their efficiency, the costs calculated for imports into Germany and the costs of the comparable fossil fuel alternatives in Germany. The countries selected are intended to be indicative of the **wide range of potential exporting nations** but should not be seen as recommendations for specific partnerships. At any rate, the results of a generic analysis would not be sufficient for such a recommendation. It is for that reason that the working group also developed a methodology for **analysing the country-related data**. Knowledge about individual countries is essential in gaining a practicable insight into the bigger picture, which in turn makes it possible to draw conclusions as to whether options for importing hydrogen are feasible in the short to medium term. The methodology is restricted to the identification of each country's general strengths and weaknesses, which provide the foundation for more in-depth analysis. With a view to enabling readers of this analysis paper to assess additional countries with speed and ease, the results are based largely on the evaluation of information that is available in the public domain.

The criteria for the country analysis (presented as an extensive set of indicators) are the potential and local conditions for renewable energy, the energy, production and export infrastructures, and progress in the transition away from fossil fuels within the exporting country's own energy system. The assessment of the countries selected by way of example also includes the answers to the following questions: Do they already have trade links with Germany? Is their economy geared up for exports? Is their population supportive of hydrogen projects? Figure 3 illustrates that each of the countries investigated has different strengths and weakness – just as the transport options do too.

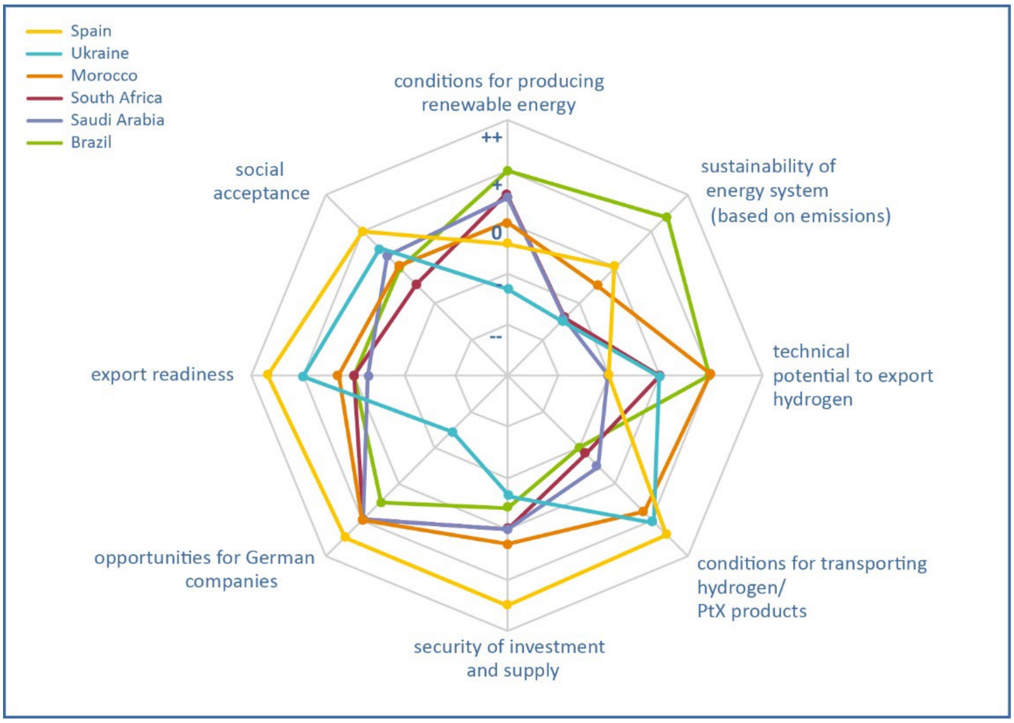


Figure 3: Overview of the results of the country analyses (source: own diagram).

Successful hydrogen **partnerships** must be established **on an equal footing**, meaning that both the exporting and importing country gain from the added value and can reap the rewards of additional benefits. After all, these kinds of arrangements only ever last in the long term if they involve a win-win situation for both parties. It is also important to consider the amount of renewable energy **each country needed** to remove fossil fuels from its own energy system. Other important factors include potential **conflict over resources** (such as land or water), **legal security** for all stakeholders and compliance with **environmental and labour standards** when planning and implementing projects.

Overcoming economic and regulatory obstacles

Technical, economic and regulatory challenges stand in the way of an effective and efficient transition to the hydrogen economy. Substantial investments are required to set up entire chains for imports that cover every stage – the production of hydrogen, the conversion of the energy carrier into a form that is suitable for transportation (e.g. through liquefication), the transportation itself, the arrival of imports in Germany and their domestic distribution. Investments of this magnitude can be incentivised by establishing a **reliable economic framework** that would make the use of (green) synthetic energy carriers competitive with fossil energy carriers in terms of the costs involved and make **investments secure** over the long term. Putting together viable **business cases** is a challenge, as is the fact that costs drop rapidly in line with technology being advanced and scaled as its use becomes more widespread over the course of several years. For example, first movers making early investments into hydrogen technologies have to compete in the long term with providers who will be able to rely on more efficient technology or transport solutions at more affordable prices a little further into the future. Purchase guarantees in the form of contracts for difference – as provided by the “H2Global” funding mechanism – can provide a useful way of **offsetting the financial risks involved in entering the market early.**

The fact that the international transportation of hydrogen by ship and pipeline has never been sufficiently and consistently **regulated** before needs rectifying. Beyond that, the creation of transparent, **trusted certification** with longevity is a priority. This should ensure that the requirements for green hydrogen and its synthesis products are actually being met across supply chains globally as an international hydrogen market emerges. Associated **information and information and documentation** will also need to be created. Care must be taken, however, to avoid discouraging investors with excessive regulatory requirements at the early stages, when the market is still ramping up. Otherwise, investors will not invest altogether or at the very least take their investments to other markets and countries. Ensuring that the regulations work in favour of investors in the beginning is certainly not an excuse for disregarding the environmental and social requirements for products and hydrogen projects put forward for certification, however. As far as the working group is concerned, there are two broad approaches here:

- **Large-scale pilot projects** could be created as a way of identifying the requirements for certification, developing the criteria for individual products and phases along the value chain, and ultimately setting up representative value chains. The steps required for certification could then be made mandatory for the projects to follow. In this case, pilot projects must be set up such that they would make it possible to enter the market with relevant volumes of hydrogen.
- The second approach is based on a **model of market phases** that sets out criteria of varying difficulty for different market phases (e.g. market entry, market ramp-up and market diffusion). It is important that the criteria for all the market phases are defined and set in stone early on. They should be communicated with transparency and risks for first movers should be minimised through the aforementioned contracts for difference or grandfather clauses. All of these measures allow investors and producers to make plans they can feel confident in. Care should be taken with regard to negative dependencies that could lead to unwanted lock-in effects.

Given that there is a certain level of insecurity surrounding the market ramp-up of a hydrogen economy, the creation of the legal and economic framework needs to involve specific mechanisms that **allow for adjustments to be**

made. A successful transition to the hydrogen economy requires the system to be **sufficiently reliable for market players**, **space to research and learn**, and a **willingness among stakeholders to act with flexibility** so that processes can be updated in a targeted manner and so that mechanisms for implementation can be reliably developed on an ongoing basis.

Using opportunities strategically

Developing a green hydrogen economy in Germany is a challenging endeavour. Given the short space of time available for this complex process, it is essential that all the different stakeholders from politics, industry and society **work together** and **consistently make progress**.

With the right approach, **hydrogen can be so much more** than just an **energy carrier and raw material**. A properly developed green hydrogen economy will be able to have a lasting **impact on policies surrounding the environment, industry and development**. The creation of a hydrogen infrastructure that crosses European borders could also improve cohesion within the European Economic Area and strengthen the continent’s energy system.

1 Introduction

At present, there is general consensus that the future demand for hydrogen in Germany will exceed the volume produced domestically. In this case, Germany will need to import a substantial share of its hydrogen from other countries to meet that demand. With the aim of reviewing the options and challenges associated with this starting point, the working group "Hydrogen Economy 2030" of the "Energy Systems of the Future" (ESYS) Academies' Project set about answering the following **questions** between January 2021 and July 2022:

- Which transport options could be used to import green hydrogen and its synthesis product (e.g. methane, methanol and ammonia) into Germany?
- What costs are associated with making imported green hydrogen available in Germany?
- Which regions have the potential to be considered as hydrogen export partners?
- What technical implementation requirements need to be met and what action needs to be taken to set up a transport infrastructure for importing green hydrogen into Germany by 2030?
- Which specific environmental, safety and regulatory aspects need to be considered for these international transport routes, especially given that they will mostly have to be newly created?
- How much of the domestic demand in Germany can be covered by imports by 2030?
- How do the import routes investigated contribute to the diversification of the energy supply in Germany?

It is not possible to cover the full extent of the potential challenges associated with transportation and imports in this analysis paper. Instead, it is intended to **introduce the topic** with a narrower focus on the transport options. In that respect, it covers the transportation of hydrogen and its synthesis products to Germany by ship and by pipeline. It follows a **terminal-to-terminal approach** which analyses the transport options from the export terminal in the country of origin to the provision of the products at the import terminal in Germany.

When it comes to transporting hydrogen and its synthesis products, the way in which they are produced in principle has no bearing on their transportation. Nevertheless, the working group “Hydrogen Economy 2030” did decide to **focus** on **green hydrogen**[8] and consider production chains with zero greenhouse gas emissions for its synthesis products wherever possible in order to stress their relevance for the transformation of the energy system and the attainment of climate neutrality in Germany by the year 2045. When the various hydrogen production costs are being considered, however, the analyses of the transport options and routes can also be applied to hydrogen created from natural gas (grey hydrogen) or hydrogen created from natural gas combined with carbon capture and storage at the production stage (blue and turquoise hydrogen).

Structure of the analysis paper

Section 2 introduces the expected **demand for hydrogen** and its **synthesis products** in Germany in 2030 and 2045 and presents the proportion of that volume that is expected to be imported. In **Section 3**, the ESYS working group “Hydrogen Economy 2030” identifies promising **options for importing** hydrogen and its synthesis products, which are presented in the form of brief profiles. **Section 4** outlines the results of the **quantitative analysis** of the transport options. The authors’ own modelling calculations detail the costs for the production and transportation of the energy carriers and raw materials (without factoring in the distribution infrastructure) and the energy efficiency levels of the conversion chains along with their main influencing factors. In **Section 5**, **qualitative criteria** are introduced for the transport options, including safety aspects, environmental impact, timescale and the feasibility of the relevant import solution from a political and regulatory perspective. **Section 6** provides an **interim summary** by drawing conclusions based on the quantitative and qualitative analyses and identifies which transport options could be most relevant for ramping up the hydrogen economy in Germany by 2030.

Section 7 shifts the focus onto more practical aspects of the implementation by presenting specific import routes for (green) hydrogen and its synthesis products. **Country analyses** are presented as examples of potential exporting countries in relevant partner regions. The findings are presented in the form of profiles. The analyses include the conditions for producing renewable energy, the production and transport infrastructures required for exporting hydrogen, and the level of acceptance among the general public in each of the countries. The selection of countries analysed is not

8 In the definition used here, green hydrogen means hydrogen generated through electrolysis, i.e. using electricity to split water into hydrogen and oxygen. To ensure that the production chain is climate-neutral, the electricity used for the process must come from renewable sources exclusively. Grey hydrogen is produced from fossil fuels (natural gas) using the traditional steam methane reformation method. Blue hydrogen is produced in the same way as grey hydrogen, but the by-product carbon dioxide (CO_2) is captured and stored for a long time and mostly underground (CCS) or captured and utilised as a raw material (CCU), for example in the chemical industry. Turquoise hydrogen is produced from natural gas using a thermal process called methane pyrolysis. The solid carbon produced in the process has to be used in building materials, for example, that will be in use for a very long time if turquoise hydrogen is to be valued as a low-emission or zero-emission option.

intended to be fully representative. By giving examples from various regions all around the world, however, the countries are representative of different distances away from Germany. In addition, the specific conditions in the countries considered do provide some insight into the implementation of transport options that appear to be most suitable. The methodology used for the country analyses is not limited to the examples covered in this analysis paper and can be applied to other countries or other combinations of exporting country plus transport option.

Building on the results presented in Sections 2 to 7, **Section 8** explains the **obstacles and challenges** that are currently standing in the way of importing hydrogen and its synthesis products into Germany and will need to be overcome if a hydrogen economy is to be developed by 2030. This section covers technological considerations, action required to adjust the regulatory framework, economic challenges and infrastructural difficulties. The conclusions to this analysis paper is presented in **Section 9**. The key results from the research are captured there in **concluding statements**. A deduction is drawn as to whether transport options have the potential to play an important part in the development of a hydrogen economy by 2030 or are not expected to be fully effective until further into the future.

2 The future demand for hydrogen and imported hydrogen in Germany

How much hydrogen will Germany need if it is to reach its climate targets? To put the volumes required into context, it is worth starting with an overview of Germany's current demand and comparing that to the level of demand expected in 2030 and in 2045, by which point Germany is aiming to be climate-neutral. When it comes to meeting the demand, the total volume required is not the only relevant information. It is also important to have an understanding of the proportion of domestically produced hydrogen and imported hydrogen and how a corresponding infrastructure for imports might be structured. If the significant increase in demand for (green) hydrogen and its synthesis products is to be reliably met – from the year 2030 onwards in particular – the scenarios for climate neutrality suggest that it will be essential to strike the right balance between domestic production and additional imports from inside and outside of the EU.

2.1 Demand for hydrogen

As it stands, approximately 1.7 million tonnes of hydrogen (around 55 terawatt hours) are consumed in Germany every year.[9] In addition to that volume, 200,000 tonnes of hydrogen bounded in raw materials like ammonia and methanol[10] are imported. This additional demand must be taken into account in the discussion surrounding the transition to products based on green hydrogen. The hydrogen being consumed in Germany at the moment is produced predominantly from natural gas using steam methane reformation. The **National Hydrogen Strategy** adopted in Germany in 2020 sets out the German federal government's expectation that around 90 to 110 terawatt hours of **hydrogen will be needed by 2030**[11]. In other words, the demand is expected to roughly double. Some of that hydrogen is to be produced through the climate-neutral electrolysis of water using renewable energy, with plans to install electrolysis systems with a total output of 5 gigawatts. This corresponds to around 14 terawatt hours of green hydrogen being generated domestically every year, which will require approximately 20 terawatt hours of renewables-based electricity.[12] The current federal government has, however, issued an "ambitious update" to this strategy and is now aiming to double that original

9 BMWK 2019.
10 World Bank 2022.
11 Presuming 4,000 full-load hours and an electrolyser efficiency rating of 70 % (cf. BMWi 2020, page 5).
12 Cf. BMWi 2020b, page 5.

target for the electrolysis capacity to 10 gigawatts per year by 2030 for the purposes of domestic hydrogen production.

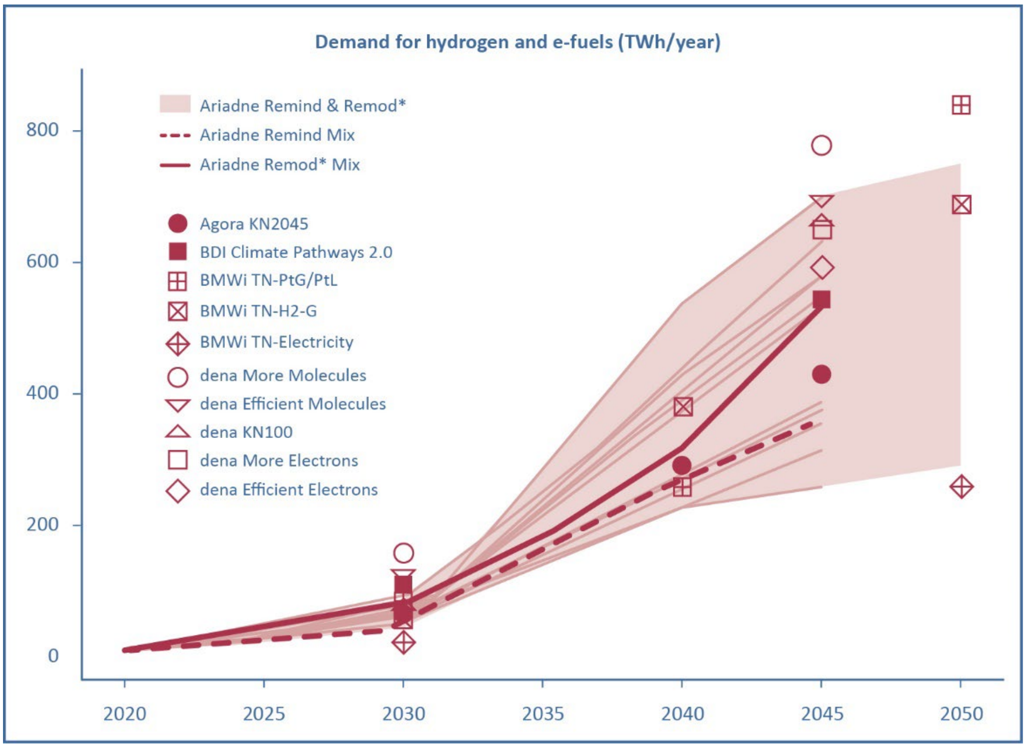


Figure 4: Range of demand for hydrogen and e-fuels by 2045 or 2050 based on different scenarios for achieving climate neutrality in 2045 or 2050 (source: Kopernikus project Ariadne: Ariadne 2021c).

Various **scenario studies** also offer insight into how the demand for hydrogen and its synthesis products in Germany might grow in the future. Each of them has modelled scenarios for Germany achieving zero greenhouse gas emissions by 2045[13]: The studies analysed suggest that the demand for hydrogen and its synthesis products will increased to between 45 and 100 terawatt hours by **2030**.[14] This range overlaps with the expectation set out in the National Hydrogen Strategy, with that estimate corresponding to and even slightly surpassing the top end of this range. The studies consider the use of hydrogen as both materially, for example as a raw material or base chemical in the chemical industry, and as energetically, for example to fuel direct reduction in the steel industry, albeit to a much lesser extent to start with compared to in 2045.

According to the **scenario studies**, the demand is expected to increase significantly **after 2030** because more and more production and energy processes and transport links will be becoming climate-neutral by that point. Since it is difficult and even impossible to remove fossil fuels from some processes relating to aviation, shipping, heavy goods shipping and the like when

13 Cf. BDI 2021; dena 2021; Ariadne 2021a; Prognos/Institute for Applied Ecology/Wuppertal Institute 2021.

14 43–81 TWh (cf. Ariadne 2021a, page 179); 64 TWh (cf. Prognos/Institute for Applied Ecology/Wuppertal Institute 2021, page 27); 69 TWh in the central scenario (cf. dena 2021, page 21, 300) and 100 TWh (cf. BDI 2021, page 20 ff.). The number of scenarios modelled (in other words, the number of potential routes for achieving climate neutrality by 2045) differs between the studies. Ariadne models 12 scenarios, while dena models one central scenario and four different paths. The BDI and the three institutes commissioned by Agora Energiewende each model one scenario.

relying on direct electrification, there will also be greater demand for solutions that use molecules with climate-neutral production processes. In the scenarios set out for Germany in the aforementioned studies, the demand for hydrogen and its synthesis products will consequently increase between 2030 and **2045**, when demand is expected to reach 420 to 660 terawatt hours.[15] According to the 12 scenarios presented in total by the Kopernicus project "Ariadne", the demand could be even higher than that since the range extends from 250 to 700 terawatt hours[16], depending on how high the efficiency gains are and the extent to which direct electrification is being relied upon in each scenario, for instance.

2.2 Import quotas

Looking at the high demand from 2030 onwards, it can be assumed that a significant proportion of hydrogen and its synthesis products will need to be imported into Germany in the future. One reason for this is that there is limited space in Germany to extend the capacity for generating electricity from renewable sources, which puts space limitations on electrolysis and other electricity applications. Meanwhile, other countries and regions have more favourable conditions for renewables that allow hydrogen to be produced by electrolysis much more cost-effectively. It is not possible to ascertain exactly what **proportion** of the overall demand for hydrogen and its synthesis products will need to be **imported** in **2030**, however. In the scenarios for climate neutrality in 2045 presented in the studies considered, the total volume of hydrogen and synthesis products expected to be imported ranges between 50 and 90 % of the total demand calculated for 2030. The proportion of pure hydrogen and synthesis products in this total volume to be imported varies greatly across the studies.

- The BDI is not expecting pure hydrogen to be imported by 2030, but does suggest that 95 % of the synthesis products required will be imported. Those imports would then cover around 55 % of the total demand for hydrogen and its synthesis products anticipated by the BDI for 2030 (approximately 100 terawatt hours). The rest of that demand would be covered by production within Germany.[17]
- Conversely, the study commissioned by Agora Energiewende suggests that imports of synthesis products will be minimal in 2030, while around 70 % of the hydrogen required will be imported by that point. In that case, that figure corresponds to the total import quota for hydrogen and its synthesis products, with the total demand calculated to be around 64 terawatt hours.[18]
- In the pilot study conducted by dena, no differentiation is made between hydrogen and its synthesis products. However, the total volume expected to

15 423 TWh (cf. Prognos/Institute for Applied Ecology/Wuppertal Institute 2021, page 27); 542 TWh (cf. BDI 2021, page 20 ff.); 657 TWh in the central scenario (cf. dena 2021b, page 21, 300).
16 Ariadne 2021a, page 180.
17 BDI 2021, page 20.
18 Prognos/Institute for Applied Ecology/Wuppertal Institute 2021, page 26 ff.

be imported in 2030 is 69 terawatt hours, which equates to around 90 % of the overall demand.[19]

- The Kopernicus project “Ariadne” estimates that 28 terawatt hours of hydrogen will be imported in 2030[20] and points out that synthesis products will only start to be imported after that point.[21] Across the different scenarios, the calculated total demand for hydrogen and its synthesis products in Germany ranges from 43 to 81 terawatt hours.[22]

The assessments for **2045** are closer together. According to the studies, the total volume of hydrogen and synthesis products that will be imported will be between 75 and 90 %.[23] The Ariadne modelling across almost all of the scenarios suggests that hydrogen and synthesis product imports will exceed domestic production from 2035 onwards.[24] Modelling by BDI and Agora Energiewende, which both differentiate between hydrogen and its synthesis products in their import quotas, indicates that 95 % of the synthesis products required and around 60 % of the green hydrogen required will be imported in 2045.

There is a great deal of uncertainty surrounding the demand figures and import quotas for 2030 and, even more so, 2045 because these figures are dependent on future developments in a highly dynamic field in which there are still many phases of technical and logistical development to be completed. What the scenarios studied do reveal, however, is that it is expected that **imports will be required on top of domestic production** in order to **meet the demand** for hydrogen and its synthesis products **in Germany in the future** even if it is possible to build up the capacity to produce hydrogen through electrolysis domestically within a short space of time.

On that basis, there is general consensus among experts and other responsible parties from the worlds of science, industry and politics that **the door must be opened to imports by 2030**. This is the only way to **ramp up a German hydrogen economy** with European and international links and, based on our current perspective, the only way to meet the increased demand after 2035.[25] That means it needs to be made possible for an **initial infrastructure to be set up** within the current decade. This will also require the creation of initial hydrogen partnerships with supplying countries, which could come in the form of agreements setting out volumes to be supplied or investments in joint pilot projects.

19 dena 2021, page 21, 300.
20 Ariadne 2021d, page 10.
21 Ariadne 2021b, page 190.
22 Ariadne 2021b, page 179.
23 Cf. BDI 2021, page 20; cf. dena 2021, page 21, 300; cf. Ariadne 2021b, page 197; cf. Prognos/Institute for Applied Ecology/Wuppertal Institute 2021, page 26 ff.
24 Cf. Ariadne 2021b, page 190.
25 Cf. e.g. BMWi 2020b; Ariadne 2021c; Ariadne 2021d; BDI 2021; BMWK 2021; dena 2021; NWR 2021 and PtJ 2021.

3 Overview of the transport options considered

In this analysis paper, pure hydrogen (in gas and liquid form), liquid organic hydrogen carriers (LOHC) and the synthesis products methane, ammonia, methanol and Fischer-Tropsch products are assessed in depth as transport media (cf. Figure 5). The analysis covers the conversion of hydrogen from gas form into liquid form and into its synthesis products in the exporting countries and the dehydrogenation of the transport media in Germany, as required for some of the transport options. Unlike, the infrastructure required to distribute the products within Germany does not form part of the analysis.[26] The generation of electricity from renewable sources prior to transportation and the useable energy contained in the hydrogen provided at the export terminal or its synthesis products are considered in generic terms, however. This makes it possible to compare the transport options and draw general conclusions about their feasibility regardless of the specific framework conditions in the producing countries, at the ports where imports arrive and so on.

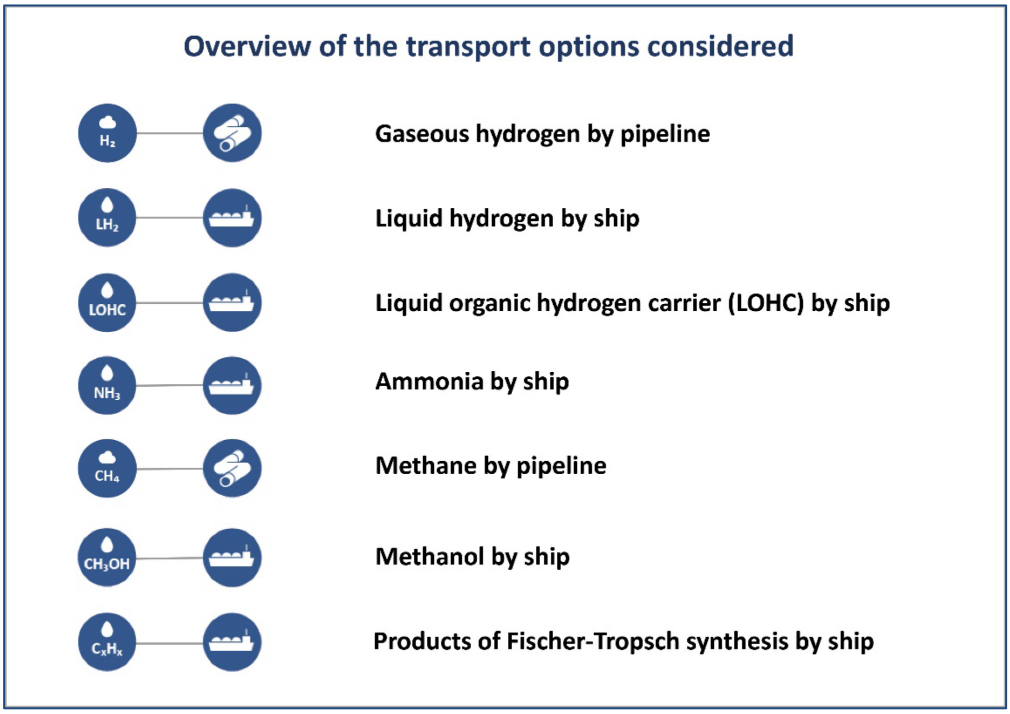


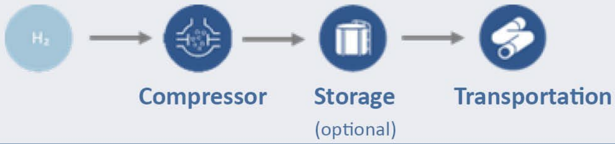
Figure 5: Overview of transport options analysed (source: authors' own diagram).

26 The distribution network does need to be considered when specific projects are being implemented, however. The way in which it is set up determines whether or not it is possible to supply end users directly. It also has an impact on the financial and staff resources required and in turn plays an important part in the decision as to whether transport options are indeed feasible and competitive.

The following options were explicitly not explored: the transportation of ammonia and methanol by pipeline, the transportation of liquid methane by ship and the blending of hydrogen in natural gas pipelines. When it comes to transporting ammonia and also methanol, strong resistance against the construction of pipelines due to their toxicity can be expected. Based on the findings of the analyses performed, transporting methane by ship would not be competitive in energy or financial terms due to the fact that it would also need to be liquefied after its synthesis. It is more expedient to transport green hydrogen by pipeline on its own than to blend it. This is partly because blending hydrogen devalues the product commercially[27] and extra time and money is required to separate the hydrogen once it has been transported via a natural gas pipeline.

27 The value is commercially higher otherwise because hydrogen is currently produced largely from natural gas and this does not look set to change any time soon, while remuneration for green hydrogen is different.

3.1 Gaseous hydrogen by pipeline



Strengths: Highest efficiency, high purity | **Weaknesses:** No extensive, specific regulations or existing hydrogen transportation infrastructure in place

Conversion chain: Gaseous hydrogen can be transported by pipeline if it is compressed. Compressors are relied upon to generate the pressure required to transport the gas. Due to technical aspects, such as those concerning the material stability of the pipeline casing, the operation should be **permanent** and with a consistent pressure. As green hydrogen is produced using electrolysers that obtain electricity from fluctuating renewable energy systems, the fluctuations have to be offset. One solution is to install a large-volume hydrogen storage tank at the feed-in point. Alternatively, extraction can be adjusted to match the fluctuating feed-in. This option would avoid any storage tank costs but would reduce the capacity to which the pipeline is used. When it comes to **onward distribution**, the compressed hydrogen can be fed directly into a hydrogen distribution network or filled into trailers for transportation via HGV or train when it reaches the end of the pipeline.

Efficiency: The conversion chain is **highly efficient**. The most significant loss of energy is caused by the operation of the compressor pumps. Some energy is lost during storage and transportation, but this is minimal.

Implementation time: At present, there is **no infrastructure for importing compressed hydrogen** in Germany or the rest of Europe. It is possible, though, that existing natural gas pipelines could be repurposed. If there is no need for planning or routing pipelines, the costs and time required for this option drop significantly. There is also the fact that Germany already has relevant experience of pipelines being used for domestic hydrogen transport (230-kilometre pipeline network in the Ruhr region), so the safety standards are in place and the practicalities have been tested out. It would appear to be relatively easy to meet the **political and regulatory requirements** if existing networks were being drawn on because the existing regulations and contracts in place for transporting natural gas could provide a solid foundation. If the pipelines were to be repurposed, it may be necessary to obtain a new operating licence, however. Taking all of this into account, the existing pipelines could be **repurposed** within **around five years**. Meanwhile, a timeframe of **around ten years** would apply in the event that **new pipelines** had to be built to allow time for planning, authorisation and construction.

Application range: Compressed hydrogen **can be used directly** across all hydrogen applications. If hydrogen is required in liquid form, liquefication can take place on site in decentralised units. Since the hydrogen is not converted into other substances or absorbed by other carrier materials during transportation, there is little chance of it being contaminated. As a result, it generally meets all **purity requirements** in the industrial and mobility sectors (including the requirements that apply to PEM fuel cells) without the need for elaborate purification processes.

3.2 Liquid hydrogen by ship

Strengths: High purity | **Weaknesses**: Extensive development required

Conversion chain: Once hydrogen has been liquefied, it can be transported by ship in special insulated tanks. The volume of hydrogen is reduced significantly in relation to the amount of energy being transported. One **unavoidable technical component** in this transport chain is the liquefier that converts hydrogen into a cryogenic, liquid state (at a temperature of around -253 degrees Celsius). Selecting the right materials for the shipping tanks and storage facilities at the port and reducing the boil-off losses caused by hydrogen evaporating are **major challenges** associated with this particular option. The hydrogen can be **distributed** by trailer when it has arrived at the port and supplied directly to buyers from there. Alternatively, liquid hydrogen can be converted to gas using an evaporator and fed into the distribution network for gaseous hydrogen.

Efficiency: The most significant loss of energy occurs when the hydrogen is liquefied. It may be impossible to avoid some of the hydrogen evaporating in transit, but solutions have already been developed that allow for that hydrogen to be used directly to propel the carrier ships. Despite that fact, this transport chain is **less efficient** than the transport chain for gaseous hydrogen.

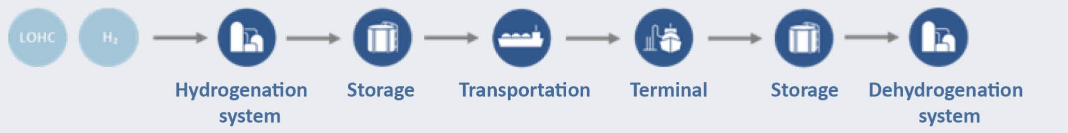
Implementation time: At present, there is **no infrastructure for importing** liquid hydrogen in Germany or the rest of Europe. It is certainly possible that other infrastructures for liquid gas could be repurposed, but there is some debate about the amount of work, time and money associated with that option.[28] Due to a lack of port infrastructure and fleet of ships, it is **expected** that it will take **around ten years** to be able to transport large volumes of liquid hydrogen in this way. A prototype of a small ship (with an approximated capacity of 100 tonnes of hydrogen) is being trialled in Japan and in Asia the development of larger tank ships (with a capacity of over 10,000 tonnes) is being in advance. Nevertheless, it is not expected that these ships will be widely available by 2030.[29] It can also be assumed that the **regulatory aspects** will involve a great deal of work since there is no specific legal framework in place for transporting liquid hydrogen. Furthermore, the authorisation process will prove challenging because the technology is new and the ships will need to be given international approval before they can be put to use. The liquefication process is also subject to some **serious**

28 Cf: https://www.presseportal.de/pm/142930/5003119/ (last accessed: 15/07/2022).
29 Kawasaki 2019

development work because it needs to be workable on an industrial scale and the energy efficiency needs to be optimised.

Application range: Liquid hydrogen can be used **directly** in liquid form or as a gas after being vaporised. There is no need for any elaborate purification process because the hydrogen is not converted in other substances during transport.

3.3 Liquid organic hydrogen carrier (LOHC) by ship



Strengths: Straightforward transportation and storage | **Weaknesses:** Low efficiency, scaling required

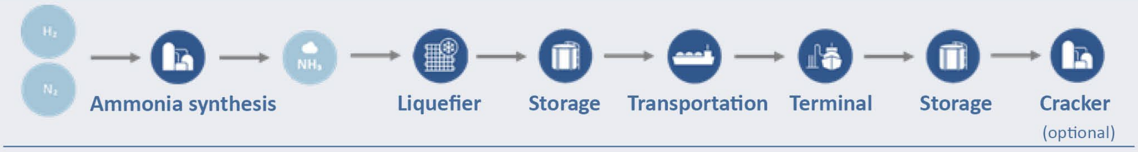
Conversion chain: Bonding hydrogen to a carrier medium (hydrogenation) like liquid organic hydrogen carriers (LOHC) is another transport option. Examples of these carrier mediums include dibenzyltoluene and benzyltoluene. Once the carrier medium plus hydrogen have been transported to their destination by ship, the hydrogen is released from the carrier medium again (dehydrogenation). It may be necessary to purify the hydrogen before it is distributed, depending on how it is going on to be used. The **carrier medium** is then **transported back to the country it was exported from** so it can be used to absorb hydrogen for transportation again. The dehydrogenation can also be decentralised and incorporated into the particular application. For this to be possible, a collection structure needs to be in place so that the carrier medium can be returned to the transport chain after the decentralised dehydrogenation. This increases the expenditure and reduces the number of cycles the carrier medium can be used for. It does offer one benefit, though, in the form of increased energy efficiency if process heat that would otherwise be wasted can be used for the dehydrogenation process (which requires a temperature of 300 degrees Celsius).

Efficiency: Significant energy losses along the chain mean that transporting hydrogen bounded in LOHC is **less efficient than transporting pure hydrogen**. **Integrated concepts** can be applied, however, to reduce those energy losses. For example, the hydrogenation process releases much heat that can be used for other applications on site to increase the overall energy efficiency. A lot of heat is also required to release the hydrogen from the carrier medium once it arrives at its destination. Using excess heat from other energy processes would be another way of improving the energy efficiency of this transport chain.

Implementation time: There is **no specific infrastructure for importing** LOHC in Germany or the rest of the EU at present. However, the material properties make it safe to assume that existing infrastructures within the petroleum industry could be exploited to some extent at least (tankers, storage facilities, port infrastructure). The existing dehydrogenation systems still need to be developed substantially and scaled up to an industrial level. The carrier medium production capacity is also insufficient. It is possible that initial pilot systems could be in operation for a market ramp-up in three to five years. But **ten years** would need to be allowed for **large-scale implementation**. There is no **legal framework** in place for the use of LOHC, but the option to make the necessary adjustments via the analogy to Diesel appears to be **relatively straightforward**.

Application range: Hydrogen released from LOHC can be used **in all hydrogen applications in principle**. The only issue would be the amount of **purification** required for some of those applications. For example, elaborate purification processes would have to be relied on to remove any residue of carrier medium before hydrogen could be used in fuel cells within the mobility sector.

3.4 Ammonia by ship



Strengths: Established technology, high efficiency | **Weaknesses:** Toxicity, limited usage compared to hydrogen

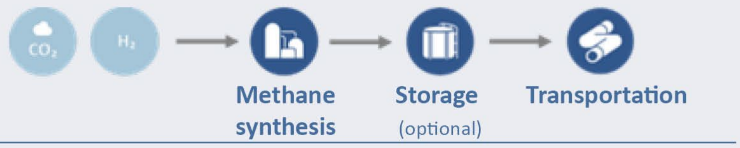
Conversion chain: Ammonia is synthesised from hydrogen and nitrogen (Haber-Bosch process), with the nitrogen required being sourced from air separation units. The ammonia can then be liquefied and transported in a chemical tanker. This process requires suitable terminals at either end and appropriate storage facilities at the ports. Ammonia is **already put to widespread use**, so established technology and existing infrastructures can be used for its onward transportation. Ammonia is predominantly used as a material in fertiliser production and in the chemical industry. It can also be used as an energy carrier and a medium for transporting hydrogen. In the latter case, a process called cracking is used to separate the hydrogen from the nitrogen again after transportation.

Efficiency: The nitrogen extraction and ammonia synthesis processes consume energy and therefore have a negative impact on the energy efficiency of this transport chain. However, the technologies used for the Haber-Bosch process and air separation are advanced with high efficiency ratings, which makes their **overall energy efficiency relatively high**. Recovering the hydrogen results in further energy losses where excess process heat cannot be exploited (temperature level at 900 degrees Celsius but can be dropped to around 500 degrees Celsius using catalysers).

Implementation time: Infrastructures for importing ammonia are **already in place** in Germany and they are used on a day-to-day basis. Given the existing infrastructure, this option would be feasible within **around two years** for use as a raw material. However, the majority of the ammonia required in Germany at the moment is not produced at central locations. Instead, it is produced in small volumes directly at the industrial site where it is going to be used. Widespread energy usage means installing new systems, which could be delayed by environmental and safety requirements. Taking into consideration the limited energy efficiency and the viability of crackers, it can also be assumed that **hydrogen recovery** will **take longer** to implement, possibly in the region of six or seven years.

Application range: Ammonia is predominantly used as a **raw material in the chemical industry** at the moment. As an **energy carrier**, ammonia can be used to fuel deep-sea cargo ships, for example. However, its toxicity means that its widespread use in energy applications is likely to be limited. If hydrogen is extracted from ammonia, an elaborate purification process is required before it can be used in applications with strict purification requirements where no ammonia residue can be present.

3.5 Synthetic methane by pipeline



Strengths: Established energy carrier | **Weaknesses**: Low efficiency, source of carbon required

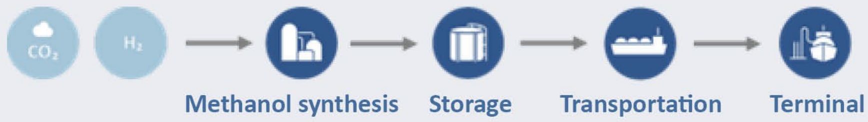
Conversion chain: Methane can be synthesised from hydrogen by adding carbon dioxide (CO_2) and transported as a substitute for natural gas through (existing) natural gas pipelines, distributed and used as an energy carrier when it arrives at its destination. The issue here is that separating the hydrogen at that point is too complex and costly. Methane can also be liquefied and transported by ship like liquefied natural gas (LNG). However, methanation of hydrogen followed by liquefication is an elaborate process involving high energy losses, meaning that this is not a cost-effective option.

Efficiency: The **energy required to extract the CO_2** is the first factor affecting the energy efficiency. It all depends on whether the CO_2 is sourced from (unavoidable) concentrated industrial sources, from biomass (where possible and expedient) or from the air by means of direct air capture (DAC). The low concentration of CO_2 means that the last of those options requires much more energy. Further energy is lost during the methanation process. Conversely, the transportation of synthetic natural gas by pipeline only involves minimal energy losses. But this transport chain is still less efficient than transporting pure hydrogen on the whole.

Implementation time: One major advantage of converting hydrogen to methane is that **existing infrastructures** can be used for its transportation **without any modification**. When it comes to the **regulatory framework**, the similarity to natural gas means that the extensive regulations already in place for natural gas can be applied without requiring any major updates. These circumstances mean that this transport option could be **implemented extremely quickly**, within **two years**, provided that the CO_2 can be sourced from unavoidable industrial point sources and made available for the production of methane at the methanation site. If the carbon dioxide is to be sourced from the air (by means of **direct air capture** – DAC), the implementation time is extended to **around ten years** because that technology is not yet available on a large enough scale.

Application range: Synthetic methane can **replace fossil fuel natural gas** as an energy carrier and raw material in industrial applications. Key applications within the energy system include gas power plants, industrial furnaces and heating systems.

3.6 Synthetic methanol by ship



Strengths: Established energy carrier | **Weaknesses:** Low efficiency, source of carbon required

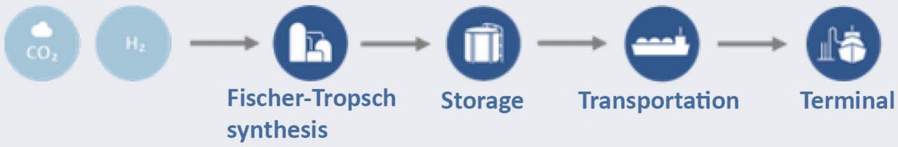
Conversion chain: Methanol is another of hydrogen's synthesis products. It is synthesised from hydrogen and carbon dioxide (CO_2). Liquid methanol is stored in storage tanks at the port to start with, before being loaded onto chemical tankers. After it has reached its destination, the methanol can be **distributed** immediately via existing routes used to distribute chemical raw materials (with transportation by trailer and train as two options). Methanol is a common chemical raw material, which can also be used as an energy carrier. Extracting the hydrogen (dehydrogenation) is so elaborately, however, that the process has not been considered any further within this analysis. In theory, methanol could also be transported in a product pipeline. A considerable amount of time would be required to establish the necessary infrastructures, however, since they are not already in place. It is also expected that the potential applications would be limited, so this option is not considered to be particularly expedient.

Efficiency: As is also the case for methane, the question of whether the **CO_2 comes from point sources** or **direct air capture** has a critical impact on the energy efficiency level. The methanol synthesis has also a detrimental effect on energy efficiency. However, the energy consumption required for transportation tends to be low.

Implementation time: The infrastructures for importing chemicals, including methanol, are already available in Germany and Europe and could be **used immediately**. However, those infrastructures are only appropriate if the methanol is going to be used materially. In order to use the methanol as an energy carrier, these infrastructures would have to be upgraded and converted in line with the relevant technologies required to exploit it. Working on the basis of the existing infrastructure for imports, this option could be **implemented quickly**, **within the space of two years**, provided that the **CO_2** can be sourced from **suitable point sources** and made available cost-effectively at the sites where methanol is synthesised in the exporting countries. In a similar situation to methane, if the **CO_2** is to be sourced **from the air**, the implementation time can be expected to be extended to **around ten years** because that technology is not yet available on an industrial scale. The fact that **a regulatory framework** for transporting methanol as a basic chemical **is already in place** is an advantage, since it can be assumed that no changes need to be made.

Application range: Methanol is very **versatile in its usage**. Methanol produced synthetically can provide a replacement for fossil raw materials used within the chemical industry and be used as the base for fuels, plastics, textiles, cosmetics and more. Methanol and its synthesis products like dimethyl ether can also be used directly as energy carriers, for example as fuel in combustion engines or in fuel cells.

3.7 Products of Fischer-Tropsch synthesis by ship



Strengths: Established energy carrier | **Weaknesses:** Low efficiency, source of carbon required

Conversion chain: The final transport option to be considered is the creation of a synthetic replacement for crude oil by means of Fischer-Tropsch synthesis (FTS). This is another process that requires hydrogen and a source of carbon in the form of CO_2. The mixed fraction of hydrocarbons with different chain lengths created by FTS, the product of Fischer-Tropsch synthesis, can be transported using the existing infrastructures within the petroleum industry (crude oil tankers and pipelines) as if it were crude oil and fed into existing crude oil storage facilities. The product of Fischer-Tropsch synthesis can then be converted into the required fuels in existing refineries and processed to produce basic chemical substances like naphtha. There is also the option to import the product by pipeline, but an existing pipeline would need to be exploited due to time and money considerations. Given that there are no pipelines in a good enough condition in Germany or Europe already, this option has not been explored separately.

Efficiency: Efficiency losses occur in particular in Fischer-Tropsch synthesis. Another important factor is the energy required for sourcing the CO_2, with the usage of CO_2 from unavoidable point sources currently proving favourable in energy terms. Minimal energy is lost during transportation by ship and pipeline, so that aspect has little impact on the overall efficiency level. Nevertheless, this option is the **least efficient** of all the options analysed. Extracting the hydrogen from the Fischer-Tropsch products would also involve significant energy losses, which makes this option far from expedient.

Implementation time: Infrastructures that already exist within the petroleum industry in Germany could be exploited for imports by ship and onward transportation by pipeline. Regarding the **regulatory framework** a quick implementation is assumed because the regulations already in place for transporting mineral oil (and its products) could be applied directly. If the existing infrastructures could be tapped into and repurposed, this option could be implemented within **around two years**, provided that the **CO_2** required comes from unavoidable **industrial point sources**. If the **CO_2** is to be sourced **from direct air capture**, the implementation time is extended considerably, to **around ten years.**

Application range: The product of Fischer-Tropsch synthesis can **replace** the **fossil fuel crude oil** in all fields of application both as an energy carrier and a raw material in industrial settings.

Deep dive: Where does the carbon come from?

Carbon is needed to produce the hydrocarbon-based energy carriers methane, methanol and Fischer-Tropsch products. The time required to implement the transport options and the attainment of the climate-neutrality target are affected significantly by the sources of CO_2 that are available for these synthesis processes. The sources have a considerable impact on the production costs, which in turn determine how competitive one transport option is compared to another option that does not depend on CO_2. They also crucially influence the implementation time and the sustainability of each transport option. If the target of developing climate-neutral energy, economic and social systems is to be met globally by the middle of the century, it is essential that fossil carbon is not used at all within the medium to long term. Instead, alternative sources of carbon need to be tapped into and the corresponding technology and processes developed.

Within this context, carbon dioxide released during the combustion of fossil carbon/hydrocarbons will only be available for a limited transition period at best. For economic reasons, an investment in carbon capture and utilisation (CCU) technology requires minimum operating or run times, which may put it at odds with global efforts to meet climate protection and sustainability targets quickly. In addition, when fossil carbon sources are used, the CO_2 emissions are separated and stored temporarily in the hydrocarbons, meaning that no CO_2 is released in the country of origin. CO_2 emissions are then released when the exported synthesis products are used in the destination country unless the CO_2 is captured and stored permanently (CCS), which requires additional technological effort and can lead to problems with acceptance. Resorting to energy-related CO_2 emissions from industrial or energy applications for the synthesis of hydrocarbon-based products and the implementation of the transport options involving them would therefore appear to stand in contradiction to climate protection commitments. That is why these options are not considered any further in this analysis paper.

CO_2 emissions from industrial processes are a different story, however. For example, the chemical reactions involved mean that CO_2 is still released even once the transition has been made to use carbon-neutral fuels to produce cement clinker. If no climate-neutral replacement for cement is developed, these CO_2 emissions will still be released even once those global targets for climate neutrality have been met. It can be concluded that they will continue to be available as a limited source of CO_2 even in the long term. In such cases, the use of CCU technologies to extract the carbon required can be expedient indeed. Continuing with the example of the cement industry, the energy output for CO_2 separation is manageable thanks to the high concentration of CO_2 in the exhaust air, meaning that CO_2 is available on relatively cost-effective terms (at a price of around €50 per tonne of CO_2)[30]. It must be taken into consideration, however, that even point sources that appear to be sizeable are quickly exhausted when synthetic hydrocarbons are being produced on a large scale. Emissions from an average cement plant amounting to 1.5 million tonnes of CO_2 per year would, for example, only be enough to fill two average crude oil tankers with the product of Fischer-Tropsch synthesis by the end of the process.[31] Furthermore, within a climate-neutral system, the same amount of CO_2 used to produce synthetic hydrocarbons would have to be captured from the atmosphere elsewhere and stored permanently.

30 The use of CO_2 from exaust air as a raw material for synthetic fuels and chemicals is presented over the cost range for CO_2 from point sources taken from literature. With €30/tonne assumed for CO_2 from cement and all other sources sitting comfortably under €100/tonne, €50/tonne appears to be a plausible average figure. (Cf. KIT 2020).

31 Roughly, this can be derived as follows: With 1.5 million tonnes of CO2, just under 500,000 tonnes of synthetic crude oil could be produced using the Fischer-Tropsch process and a typical crude oil tanker can transport approximately 250,000 to 300,000 tonnes.

The volume of carbon required is also the main obstacle standing in the way of using biogenic CO_2 emissions, such as those released during the production of bioethanol or biogas. These are concentrated point sources that should also be used where possible. They cannot, however, supply the volumes normally required for a large-scale production. The same applies to the provision of concentrated flows of CO_2 from biomass gasification (converting waste) because biogenic CO_2 from these processes is on the same level as industrial CO_2 separation in terms of costs.

When it comes to the large volumes of synthetic hydrocarbon-based energy carriers already mentioned, there is no long-term alternative to direct air capture (DAC) beyond the sources mentioned previously. However, the low concentration of CO_2 in ambient air means that separating it requires a great deal of energy. Nonetheless, it does appear to be possible to incorporate excess process heat into the process at suitable sites and thereby reduce the amount of energy required for DAC. It can be assumed, however, that it would be unlikely for the costs of DAC to be brought in line with the price of CCU technology – even if significant progress were to be made with development work. As a result, the climate-neutral hydrocarbons produced using DAC technology will be much more expensive (around €150 per tonne of CO_2 in 2030[32]). Since this will be the only option for providing the required amount of carbon in a climate-neutral way in the medium to long term, the development of DAC technology to make it suitable for widespread usage on an industrial scale is a must. The ramp-up for DAC technology will be years in the making, however, which explains why the transport options involving hydrocarbons from this CO_2 source have an extended implementation period in excess of ten years.

32 Authors' own calculations based on Viebahn 2019, Viebahn et al. 2019 and Fasihi et al. 2019.

4 Comparative calculations for the transport options

In this section, the transport options introduced in Section 3 will be compared against one another in a quantitative analysis based on indicators. Key variables include the costs for the hydrogen used and the distance to be covered when transporting the hydrogen. In order to draw conclusions about how cost-effective the options are, the costs for providing the hydrogen produced by electrolysis and imported into Germany and its synthesis products as per the calculations are compared against the costs of the comparable fossil-based energy carriers, in each case with and without a varying price for CO_2. Energy efficiency is another important parameter when it comes to comparing the transport options. As well as providing key information about the energy input required to produce and transport the energy carriers, it also indicates the raw material and space requirements, especially for upstream systems. It can be said, for example, that the less efficient an option is, the more renewable energy systems will be required to produce hydrogen and ultimately end up with the same amount of energy in Germany at the other end of the chain.

4.1 Methodology

The main **influencing factors** along the conversion and transport chains are the **systems used to convert the hydrogen** into the physical state required for transportation or the relevant synthesis product, the **means of transport** itself (ships and pipelines) and, depending on the transport option in question, any systems that may be required to **recover the hydrogen**. The costs for the electrolysis of water are not explicitly included because the hydrogen provided is taken as the starting point so that the costs can be compared across all the transport options. In other words, the costs for electrolysis are not counted as a differentiating factor. The same applies to the costs of providing the energy for electrolysis and their annual utilisation rate. These factors may vary between countries, but they can be evened out initially to make it possible to perform a basic evaluation of the transport options. Both variables are, however, taken into account implicitly in the calculations through a variation on the parameter of hydrogen costs. Conversely, the production of any nitrogen or carbon required is incorporated directly into the modelling. The final point to raise here is that the graphs depicting costs in this section always relate to the energy contained in the material that is ultimately imported, representing the energy that can actually go on to be used at the final destination. All currency information is based on values from 2020.

The modelling calculations do not directly disclose the **CO_2 emissions** released during the production and transportation of the energy carriers. Including this data does not fall within the scope of the current analysis and would require a life cycle analysis of all components because of the heavy weighting of indirect CO_2 emissions released by upstream processes. It is for this reason that individual emission reductions can only be presented by way of example in this paper (see Section 6). What can be said, though, is that direct CO_2 emissions released during production and transportation are minimal and can even be reduced to zero for the options considered here on the basis of hydrogen produced by electrolysis where the energy carriers used are based on renewable energy sources (electricity, green hydrogen, renewable ammonia and so on).

Important assumptions for the modelling calculations

The modelling calculations presented in this section are based on the following assumptions:

- A **consistent capital interest rate** of 8 % per annum is assumed for all systems.
- A price of €145 per tonne of **CO_2 obtained** through direct air capture and €55 per tonne of **N_2 obtained** through air separation have been taken as estimates for the year 2030.
- By way of example, **electricity costs in the exporting countries** have been estimated at €0.045 per kilowatt hour for 5,000 full hours of use of systems powered by electricity based on the availability of renewable electricity/hydrogen[33]. **Electricity costs along the pipelines and in Germany** have been estimated at €0.15 per kilowatt hour.
- The **depreciation and service life** is estimated at 20 years for all systems with the exception of ships (30 years), crude oil tankers (25 years) and pipelines (40 years).
- For **process heat in Germany** used for dehydrogenation of energy carriers (above 300 degrees Celsius), the costs are estimated at €0.10 per kilowatt hour. Cases in which the provision of process heat used for dehydrogenation has been assumed to be free of charge as a sensitivity form an exception.
- Heavy fuel oil (IFO 380) has been assumed as the **fuel** for the **ships** at a price of $400 per tonne, used at 50 % efficiency.

33 Combining photovoltaics and wind energy and overemphasising electricity generation are considered when deemed to be financially advantageous or a way of lowering costs. For further information on this, please refer to the reference material (Schmidt et al. 2022).

- All **shipping routes** have been assumed to involve **travel back and forth** between the exporting country and Germany. The return journey is always included in any considerations on costs and energy efficiency.
- The systems are operated on a commercial industrial scale. It has also been assumed that the **technologies** considered will all be available **industrially by 2030** regardless of the fact that they are all at different stages of development as it stands.
- With the exception of the process heat provided free of charge for dehydrogenation as mentioned previously, any potential **synergies** provided by combining processes within the conversion chains analysed or bringing in other processes are not considered.

At first glance, the electricity costs estimated in the calculations may appear to be on the high side compared to much lower rates, such as those from Saudi Arabia. In some cases, those production costs are $0.01 per kilowatt hour for PV power and $0.02 per kilowatt hour for wind power. These extremely low figures, however, only tend to apply when the power is being fed fully into the public grid and given an optimal financial situation based on an interest rate of under 2 %.[34] But if the interest rate is 8 %, for example, the electricity costs converted to euros increase to €0.0141 per kilowatt hour for photovoltaic power and €0.036 per kilowatt hour for wind power. Given an equivalent mix of photovoltaic and wind power, the price totals €0.0272 per kilowatt hour. Once expenses for system management (including battery storage) and the standalone grid required to connect consumption systems are factored in, electricity costs soon reach €0.04 per kilowatt hour based on the renewable energy production potential. Combined with a curtailment of the renewable energy production potential of at least 11%, the estimated rate of €0.045 per kilowatt hour (based on the amount of electricity consumed) is reached.

All other assumptions, the sources used and a detailed explanation of the calculations can be found in the reference material[35].

4.2 Costs for importing energy carriers (not including hydrogen production)

At the first stage of the analysis, the import costs are provided without the expenditure required to produce the hydrogen, which is assumed to be the same to make it easier to compare across all the options. The costs for all the processes after hydrogen production are included in the calculations, though. This includes the compression and liquefication of hydrogen, the hydrogenation of carrier materials and the synthesis of ammonia, methane, methanol and Fischer-Tropsch products. The costs of obtaining CO_2 and

34 Cf. IRENA 2020.
35 Cf. Schmidt et al. 2022.

nitrogen in the exporting country are also included along with any costs incurred for the dehydrogenation of carrier materials in Germany.

Figure 6 presents the costs for different energy carriers based on the distance to be covered for transportation to Germany. It is clear that **none of the transport options** can be taken as a **universal solution** from a financial perspective. In other words, a **combination of energy carriers and transport routes** would appear to be the best way of meeting the future demand for hydrogen in Germany. While the option of transporting gaseous hydrogen by pipeline is the most cost-effective option for short distances (of less than 4,000 kilometres), transportation by ship can make better financial sense for longer distances.

Another clear result of the modelling calculations is that **recovering hydrogen from synthesis products rarely makes sense financially**. In most cases, it is more expedient to use the synthesis products (ammonia, methane and methanol) directly as they are. Ammonia is the only exception here. Since it is very inexpensive to produce and transport, the dehydrogenation of ammonia is an option in principle.[36]

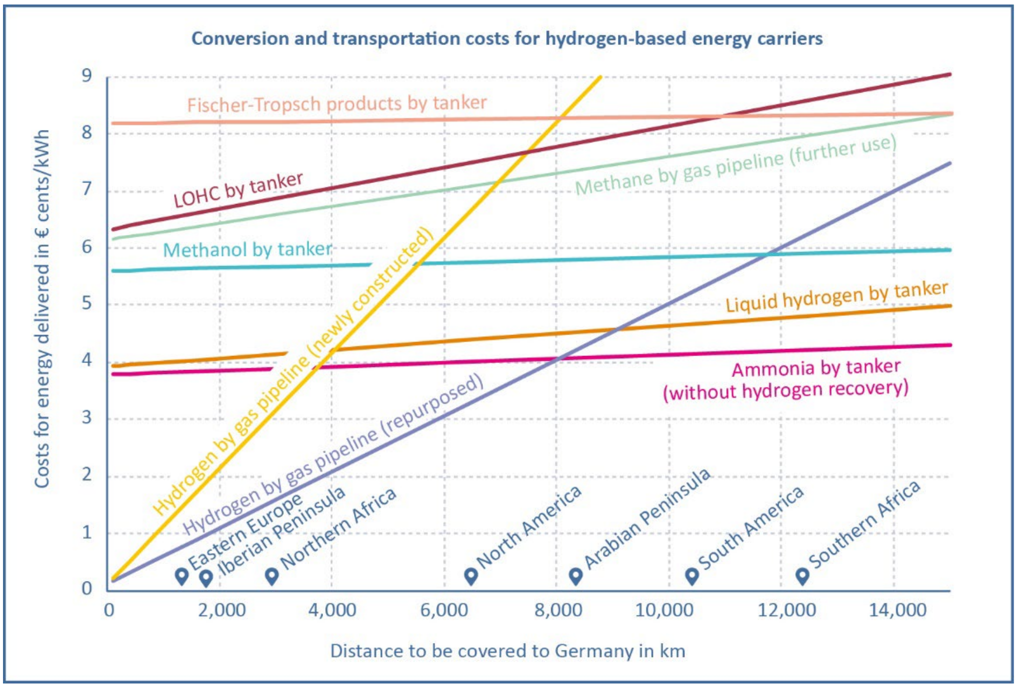


Figure 6: Conversion and transportation costs for different hydrogen-based energy carriers depending on the distance to be covered for transportation to Germany. The costs of hydrogen production are not included in the data presented in this figure. Conversely, the costs incurred for the compression and liquefication of hydrogen and the synthesis of other energy carriers (ammonia, methane, methanol, Fischer-Tropsch products) are included in the data presented in the figure[37] (source: authors' own calculations).

36 See Section 4.4 and Figure 8 for more in-depth insights into the conditions in which it might make financial sense to extract hydrogen from ammonia.

37 The distances to be covered for transportation to Germany from the example regions in this and later diagrams relate to the commercial shipping routes. In that respect, it is important to note that the distances for pipeline routes may differ from the distances presented here.

With respect to the import costs, the extent to which the transport options **depend on the distance to be covered** varies quite considerably:

- Since the costs for compressing pure hydrogen are relatively low, the use of gaseous hydrogen pipelines is very cost-effective across short distances. All other curves start with an **offset** on the y-axis that represents the cost of preparing the energy carrier to be transported. Examples include the liquefication of pure hydrogen for transportation in tankers and methanation so that methane can be transported.
- The biggest cost increase based on the distance to be covered applies to **pipelines** because all the costs continue to rise as the distance increases.
- When it comes to **transportation by ship**, meanwhile, the costs associated with investments in and operation of systems that are required to prepare energy carriers for transportation (such as liquefiers and synthesis systems) are not affected by the distance to be travelled. The (moderate) slope of the curves just reflects the relatively low costs of the actual transportation by ship itself, which also depend on the size of the ship and the amount of energy being transported.
- **LOHC tankers** take up an intermediate position. As the round trips take longer when there is a greater distance to cover, the costs for the carrier medium[38] have to be spread across fewer cycles. Of all the options, benzyltoluene has the lowest energy density of the options considered here. On that basis, the costs for longer distances rise more sharply when transporting LOHC by ship than anything else.

Figure 7 breaks down the import costs incurred for each of the transport options. The costs are broken down into:

- Expenditure on investment into conversion systems (capital costs)
- Expenditure on operation of conversion systems
- Costs for auxiliary energy required to use conversion systems
- Expenditure on supply of auxiliary materials (CO_2, N_2 and LOHC carrier medium)
- Costs for transportation of the energy carriers
- Costs associated with conversion losses

38 The calculations for LOHC technology drew on information from Prof. Peter Wasserscheid (Friedrich-Alexander-Universität Erlangen-Nürnberg/Forschungszentrum Jülich) that was provided to the authors in April 2021. The calculations are based on the carrier material benzyltoluene by way of example.

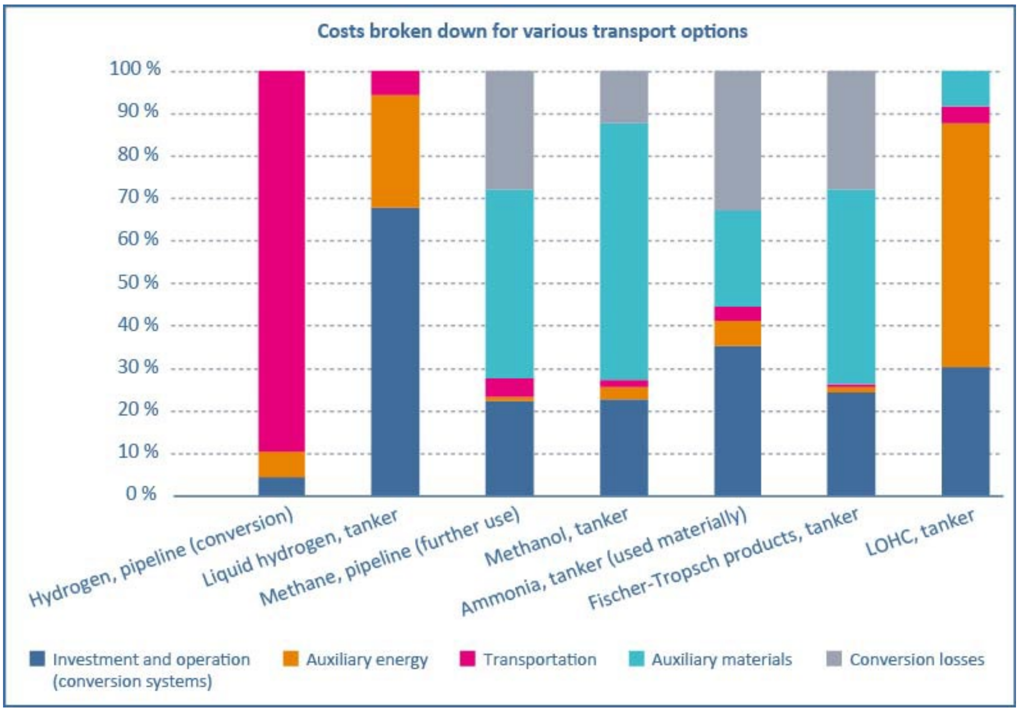


Figure 7: Costs broken down for various transport options covering a distance of 2,000 kilometres (source: authors' own calculations).

This graph clearly shows that the costs vary significantly between some of the options when broken down. With the **transportation of hydrogen by pipeline**, the costs associated with compressing the hydrogen are so low that the transportation costs are almost the only costs involved with this option. The opposite is true for the **transportation of liquid hydrogen by tanker**, in which case the investment in and maintenance of the tankers and the operation of the liquefiers account for a large proportion of the costs. Where **hydrocarbons** are being produced and transported, meanwhile, the costs for obtaining CO_2 (covered in the costs for auxiliary materials) dominate, with the assumption having been made that direct air capture would be used instead of industrial point sources and so on in the medium to long term, taking into account the target to achieve climate neutrality. Where it makes sense to use cheaper CO_2 (point) sources on a case-by-case basis, these costs can be almost halved.[39] Where **hydrogen is absorbed by LOHC for transportation**, the costs for the heat required to recover the hydrogen are significant.

4.3 Energy efficiency of the transport options

Energy efficiency is a key indicator for energy usage. It indicates how much of the energy available at the beginning and used in the country of origin (in the form of hydrogen, auxiliary power/electricity and heat) can be used in the country at the end of the transport chain in the form of the imported energy carrier. The overall efficiency is a key factor used to assess the transport options

39 For more information on this, please refer back to the deep dive in Section 3.7.

along with the costs. It indicates the amount of electricity and hydrogen to be provided in the exporting countries and gives an insight into the raw materials and space that will need to be used to expand the renewable energy systems as well as providing information about the local impact. If a transport chain is not very efficient, the synthetic energy carrier will reduce the CO_2 in the exporting countries to a lesser extent in relation to the resources required (energy, space and so on) than if it were highly efficient. This point is significant because the global demand for climate-neutral energy carriers will most likely see a sharp increase in the foreseeable future. In fact, the demand may even outweigh the availability quite considerably.

Table 1 reveals how efficient the transport chains in this analysis are. **Transporting hydrogen by pipeline** is a **highly efficient** option. The losses are minimal because hydrogen compression requires relatively little energy. The liquefication of hydrogen involves greater losses, with the **transportation of hydrogen by ship** proving much less efficient than transportation by pipeline. The transport options that involve **hydrocarbons** being extracted have a comparatively low efficiency rating because the extraction of the carbon dioxide required for the synthesis by direct air capture consumes a lot of energy. **Recovering hydrogen from LOHC or ammonia** also uses much energy. In other words, all of these options are less efficient than transporting gaseous hydrogen. The associated losses in efficiency could be avoided if it is possible to use excess process heat for the dehydrogenation. Having said that, high temperatures are required for that dehydrogenation – 300 degrees Celsius for LOHC and as much as 900 degrees Celsius for ammonia. Heat sources at those temperatures very rarely come with zero costs and will be even rarer in future as changes are made to the heat supply and production processes.[40]

40 One of the exceptions here could be deep-sea shipping. As ships are propelled, high temperatures arise that cannot be put to any other use out at sea. If the excess heat were used to extract hydrogen, it could then be used again as a fuel to propel the ships themselves.

Transport option	Distance	Process chain	Efficiency based on the usage of hydrogen	Efficiency based on the usage of renewable electricity
Gaseous hydrogen by pipeline	1,000 km	99% → 99%	98%	63%
	4,000 km	99% → 96%	94%	61%
Liquid hydrogen by ship	10,000 km	81% → 93%	75%	49%
LOHC by ship	10,000 km	99% → 94% → 73%	68%	44%
Ammonia by ship (used as material)	10,000 km	83% → 97%	80%	52%
Ammonia by ship with hydrogen recovery	10,000 km	83% → 97% → 93%	75%	49%
Methane by pipeline	1,000 km	63% → 100%	63%	41%
	4,000 km	63% → 99%	63%	41%
Methanol by ship	10,000 km	65% → 98%	63%	41%
Fischer-Tropsch products by ship	10,000 km	57% → 99%	56%	37%

Table 1: Efficiency of the transport chains analysed measured against the energy content of the hydrogen used and the renewable energy used (with electrolysis at 65% efficiency; hydrocarbons with CO_2 from direct air capture).

It is important to note that, depending on the application, the overall efficiency, that is the efficiency from creation to use, changes when more efficient technology comes into play. For example, fuel cells in vehicles are much more efficient than standard combustion engines, which shifts the overall efficiency further in the direction of importing pure hydrogen. The usage aspect does not form part of this analysis paper, however.

4.4 Cost comparison of various options for transporting hydrogen

After Section 4.2 covered import costs, this section compares the various options for transporting hydrogen against one another in detail. To start with, the various options for **importing pure hydrogen into Germany** are going to be considered in greater detail. The analysis here shows that transporting **compressed hydrogen via pipelines** is the most favourable option from a financial perspective over relatively short distances of up to around 4,000 kilometres (cf. Figure 8). However, for this option, the following aspects need to be considered as far as the pipelines are concerned: Relatively small pipelines with a diameter of around 300 millimetres and the capacity to transport a volume of around 500 tonnes per day are very expensive even when only short distances are being covered.[41] Larger pipelines with a diameter of around 1,000 millimetres and the capacity to transport a volume of around 6,000 tonnes to 7,000 tonnes of hydrogen per day are much more cost-effective by comparison.[42] Even more cost-effective still is the option of repurposing existing (natural gas) pipelines so they can be used to transport hydrogen. These can provide a more cost-effective solution than transporting liquid hydrogen by tanker ships even across longer distances of up to above 8,000 kilometres.

However, the construction of new pipelines accompanies by **clear spatial definitions** for the route. A pipeline also needs to be used at a **high capacity that is as constant as possible** so as to guarantee that a large volume of hydrogen can be transported to keep operation cost-effective. In terms of energy efficiency – or the balance of energy losses occurring throughout the transport chain – hydrogen pipelines keep losses the lowest when all the transport options are compared against one another (cf. Section 4.3).

The transportation of **liquid hydrogen by ship** only starts to be of interest financially compared to transportation by pipelines once longer distances are being covered. If there is no option to repurpose existing pipelines, the transportation of liquid hydrogen by ship would be a feasible option for distances above 4,000 kilometres or so. However, if it is possible to repurpose existing natural gas pipelines, transportation of liquid hydrogen in tankers only makes financial sense for distances above around 8,000 kilometres. Another aspect to incorporate into this comparison is that the transportation of liquid hydrogen by ship is much less efficient than the transportation of gaseous hydrogen by pipeline (see Tabele 1).

41 This is the diameter of hydrogen pipelines already in use, for example in the Ruhr region in Germany and in other locations in Europe and the USA.

42 Diameters of 1,000 millimetres are standard for natural gas pipelines such as North Stream, MIDAL and WEDAL. Some systems like OPAL have diameters as large as 1,400 millimetres.

Building on Figure 8, Figure 9 shows that in many cases having hydrogen absorbed by **liquid organic hydrogen carriers (LOHC)**[43] is generally more expensive than transporting pure hydrogen no matter what the distance. The same applies for a more theoretical scenario in which excess process heat[44] required for dehydrogenation is available at a high enough temperature at no cost (see below and Section 4.3).

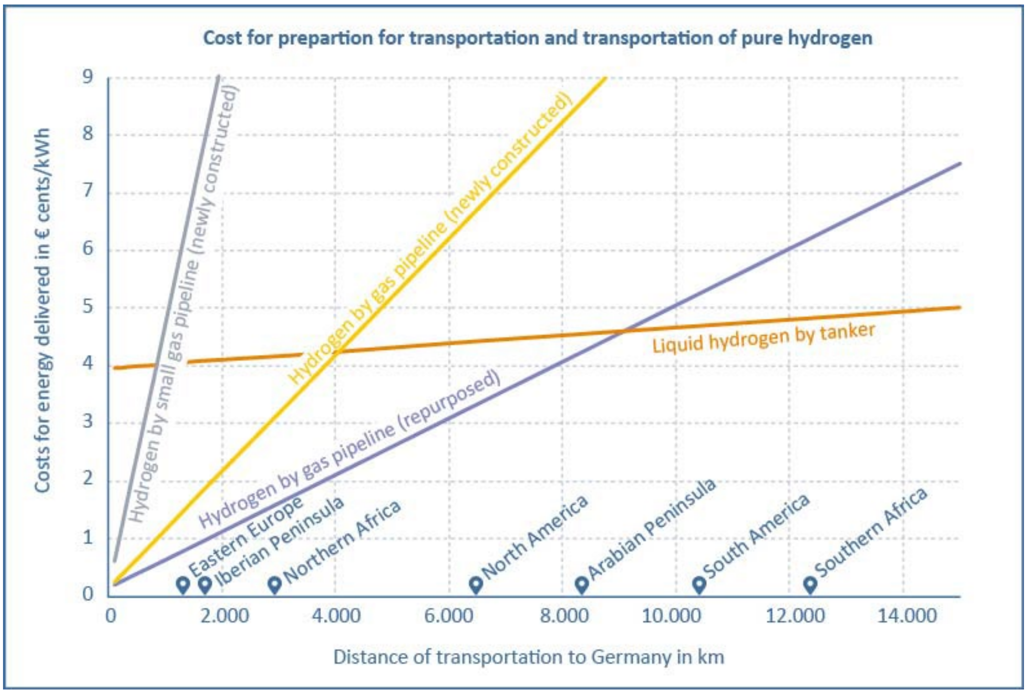


Figure 8: Costs for preparation for transportation and transportation of pure hydrogen by pipeline and by ship depending on the distance to be covered. The costs of hydrogen production are not included in the data presented in this figure (source: authors' own calculations).

43 Benzyltoluene is the example carrier material used in the modelling calculations.

44 Temperatures of around 300 degrees Celsius are required to release hydrogen from the carrier material (LOHC).

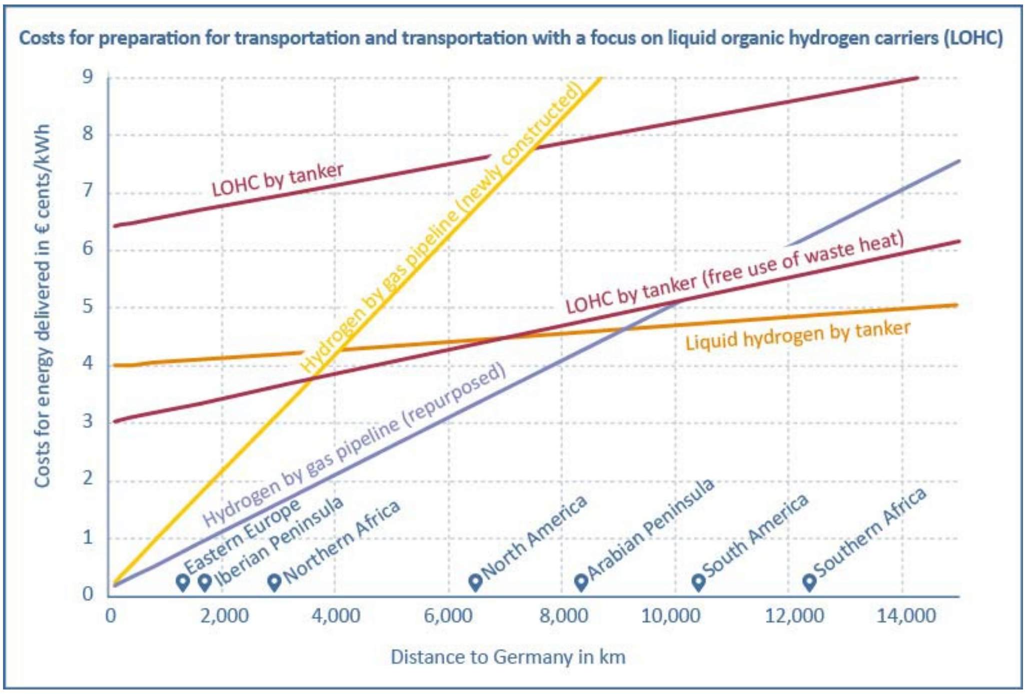


Figure 9: Costs for preparation for transportation and transportation of pure hydrogen and hydrogen absorbed by LOHC depending on the distance to be covered. The costs of hydrogen production are not included in the data presented in this figure (source: authors' own calculations).

Another option for importing hydrogen is to synthesise ammonia from hydrogen and then recover that hydrogen from the ammonia upon arrival in Germany. Despite the extra expense associated with the dehydrogenation, it can still be feasible financially because transporting ammonia by ship is generally one of the most cost-effective transport options considered (see Figure 6). This option is cost-effective regardless of the distance to be covered where the ammonia is going to be used directly as a material, but it is also cost-effective when the ammonia is being used as an energy carrier, especially when it is being imported into Germany from further afield. However, recovery of hydrogen from ammonia is a costly process that requires much energy because it relies on temperatures of around 900 degrees Celsius. As Figure 10 shows, the option of the dehydrogenation of ammonia[45] ends up being much more expensive than importing liquid hydrogen by tanker.

Figure 10 also presents the rare but theoretical best-case scenario in which excess process heat can be used free of charge to recover hydrogen from ammonia (pink line). Since the temperatures required here are very high, though, this option is not likely to be feasible in practice, as mentioned previously. The red line sets a lower limit for costs. If it were possible to develop an integrated (chemical) process in which some of the heat required to dehydrogenate the hydrogen could be sourced from other processes at no cost, it would theoretically be feasible to assume that the transportation of hydrogen by means of ammonia could be competitive with transportation by liquid hydrogen tanker. At this point, though,

45 The price assumed for the provision of process heat is €0.10 per kilowatt hour.

further research is required so it can be clarified whether it will be possible to implement this transport option in a way that is financially feasible in the future.

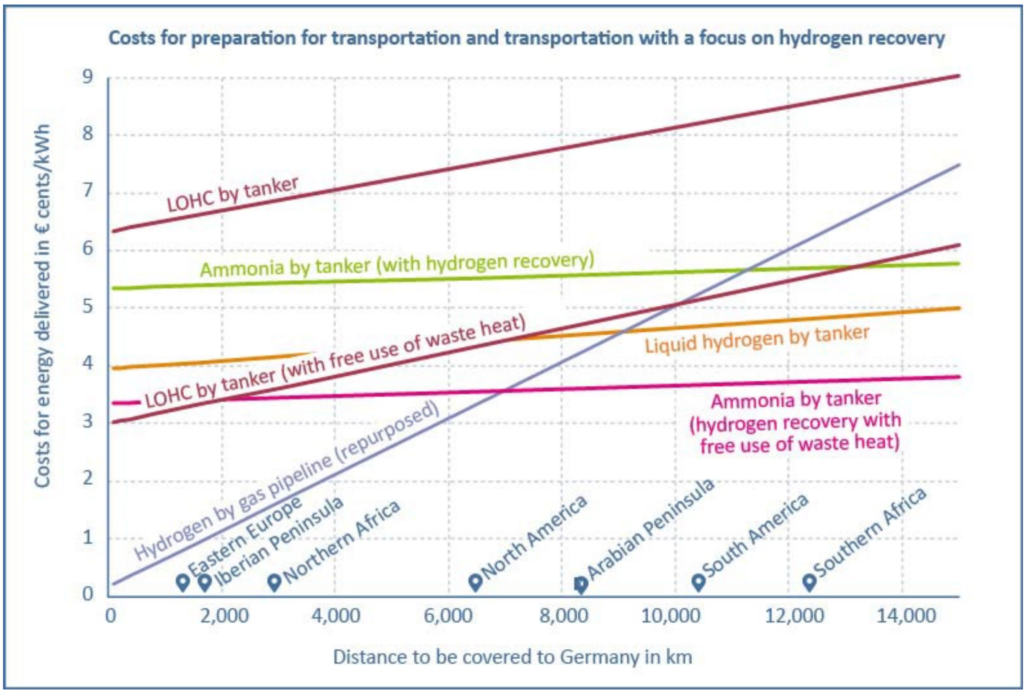


Figure 10: Costs for preparation for transportation and transportation of pure hydrogen and hydrogen absorbed by LOHC and ammonia depending on the distance to be covered.[46] The costs of hydrogen production are not included in the data presented in this figure (source: authors' own calculations).

4.5 Import costs for energy carriers compared against fossil fuel benchmarks (including hydrogen production)

For the final stage of the analysis, the import costs for the energy carriers being considered are compared against the prices of conventional energy carriers. Varying production costs for green hydrogen and different distances to be covered are factored in. The values for the fossil-based products being compared include a variable CO_2 surcharge. Since the prices for natural gas have risen drastically since the end of 2021, two different prices have been provided as references. The costs for hydrogen production were assumed to be between €2 per kilogram of hydrogen and €4 per kilogram of hydrogen. The lower value is based on optimistic estimates that could be feasible by 2030 given favourable local conditions, but this will rely on significant progress being made with the development of electrolysers.[47] A price of €4 per kilogram of hydrogen produced by electrolysis would be possible even now given favourable local conditions.[48] In order to determine the CO_2 prices at which synthetic

46 The price for the provision of process heat where excess heat cannot be used free of charge is €0.10/kilowatt hour.

47 Drawing on these ISE costs given favourable local conditions, the calculations indicate hydrogen production costs of around €3 per kilogram (cf. Fraunhofer ISE 2021). However, there are also studies that assume the costs for electrolysis systems and electricity will be much lower by 2030. In the best-case scenario in those studies, the hydrogen production costs are predicted to be lower than €2 per kilogram, which has been taken as the minimum rate here (cf. IEA 2021b).

48 In the calculations performed here, a price of €4 per kilogram of hydrogen would be feasible today with the following parameters in place for electrolysers: investment costs of €750/kW_el, 8% interest rate, 3% of investments/year on operating and maintenance costs, service life of 20 years with 4,000 full-load hours and electricity costs of €0.05/kWh.

energy carriers would be competitive compared to fossil-based energy carriers, CO_2 prices of €100 and €200 per tonne of CO_2 have been assumed for 2030 by way of example.

Deep dive: Costs versus prices

In this section, the costs calculated for imported hydrogen and its synthesis products are compared against the prices of comparable fossil-based products that are already established in the economic system. This comparison is essential because it is only possible to run cost calculations for the options anticipated for the future and not price calculations. Meanwhile, prices represent the current value of established products. A comparison of this nature demands a certain sensibility when it comes to reading the diagrams and interpreting the results, however.

The costs reveal the amount of money required to produce a product. But there are different types of costs depending on which aspects of the production process are included in the calculation. Common types of costs include marginal costs, which only include variable elements (such as energy and input materials), and full costs, which also include any fixed costs (such as depreciation, maintenance and insurance for systems). It is also important to consider whether these costs are being calculated for an existing system or as part of abstract modelling.

By contrast with costs, prices indicate the amount of money required to buy a product. They may differ depending on the type of buyer they apply to (such as large industrial customers, government representatives, commercial end customers and private end customers) and are not determined by production aspects. Prices can also be influenced by the demand. The difference between prices and costs, known as the margin, amounts to the provider's profit and covers other costs that are not directly related to production.

As a general rule, costs are lower than prices – at least as an average over the long term and if no subsidies can be claimed. Assuming a functioning market, there should not be a massive difference between the full costs for existing production systems and prices as an average over the long term. A comparison of this nature is not quite possible in this case because the cost calculations are only based on modelling. Nevertheless, the comparison presented here does provide clear insights into whether an option has the potential to become established on the market in the future based on financial considerations and whether the pricing structure for the various products will remain more or less the same as it is currently or if major shifts can be expected.

4.5.1 Hydrogen

Figure 11 shows the overall costs for the production and transportation of **green hydrogen** for various transport options by way of comparison with hydrogen produced from natural gas using the steam methane reformation method. Due to the drastic price rises since the end of 2021, two different prices are provided for natural gas by way of comparison. This comparison reveals that green hydrogen could be competitive in 2030 if it is produced in favourable local conditions and transported across short distances even with CO_2 prices under €100 per tonne. This is true regardless of whether existing natural gas pipelines are repurposed or new hydrogen pipelines are constructed. With CO_2 prices of €200 per tonne of CO_2, green hydrogen could even be an alternative if the production costs were higher and it was transported over greater distances.

If natural gas prices were to remain high, green hydrogen transported to Germany by pipeline would still be competitive even if the production costs were higher. This would be the case in particular if local conditions were not optimal and the costs for the necessary technology were to only drop slightly by 2030. Green hydrogen produced in favourable local conditions and imported in liquid hydrogen tankers would prove attractive financially much earlier on if natural gas prices were to stay high.

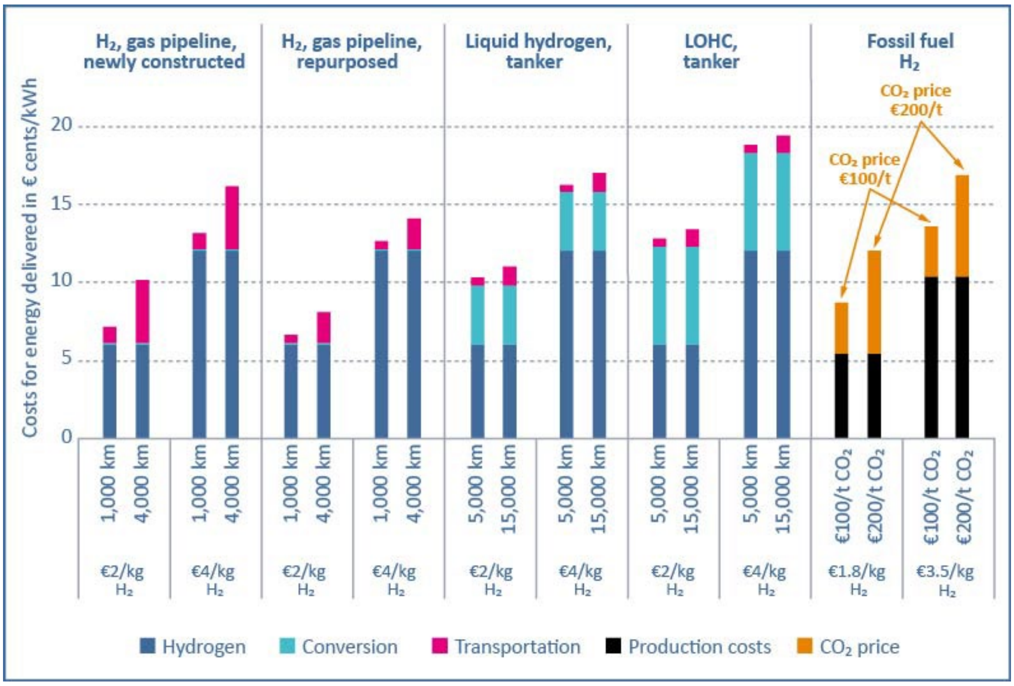


Figure 11: Costs for importing green hydrogen transported by pipeline, transported by ship or absorbed by LOHC compared to the costs of standard hydrogen. Different distances and green hydrogen production costs are presented to provide different options for the comparison. In both pipeline cases, the pipeline is understood to have a diameter of 1,016 millimetres and the capacity to transport a volume of 6,000 tonnes to 7,000 tonnes of hydrogen per day. The costs for standard hydrogen produced from natural gas using the steam methane reformation method are based on natural gas prices of €0.035/kWh (as at 2020; without CO_2 price) and €0.07/kWh (as at January 2022; without CO_2 price).[49] (Source: authors' own calculations)

Within the context of this comparison, it is important to remember that hydrogen is currently often produced from natural gas directly on the site where it is going to be used or at least close to it. The calculations for green hydrogen presented here only include the costs up to the import terminal – any costs incurred for distributing the hydrogen will apply in addition. Figure 11 once again highlights that the **distance to be travelled** is relevant for transportation by pipeline but not for transportation by ship.

4.5.2 Synthetic methane and Fischer-Tropsch products

Synthetic **methane** and **Fischer-Tropsch products** produced on the basis of green hydrogen can provide a replacement for the fossil fuels natural gas or crude oil. Yet the comparison of the costs associated with the production and

49 Cf. Prognos 2020; the industrial consumer price for natural gas in January 2022 was estimated on the basis of the development of cross-border prices. It was assumed the increase in cross-border prices was passed on in full.

transportation of these synthetic energy carriers reveals a different scenario to hydrogen. Regardless of the distance to be covered, the costs far exceed those of conventional energy carriers even when CO_2 prices are high (see Figure 12). This means that the synthetic energy carriers cannot compete with their fossil fuel equivalents in financial terms when CO_2 is priced at between €100 and €200 per tonne. There is no change to the situation even when the natural gas prices are as high as at the start of 2022.

There are several reasons behind these findings being so different to those for pure hydrogen. With fossil energy carriers, hydrogen has to be made using natural gas and is therefore classed as a derivative. But hydrogen is the source product for synthetic fuels, which means that the energy carriers have to first be synthesised from hydrogen and carbon. It is that process that makes methane and Fischer-Tropsch products more expensive than pure green hydrogen, which is only their source product. Obtaining the carbon required for this process also incurs additional costs.

Nevertheless, there are many other arguments in favour of a market ramp-up for synthetic methane and Fischer-Tropsch products. At this point, it is important to mention that existing infrastructures can be used and processes involving unavoidable hydrocarbons can be exploited. It does make sense to import synthetic energy carriers, then, if they have specific characteristics that are required for particular applications (such as their carbon content, energy density and liquid state) (refer to Section 8 for more on this).

For ease of storage and transportation, it makes more financial sense to synthesise hydrocarbons in the exporting country. Importing hydrogen and then performing the synthesis in Germany could be a cost-effective option if cheap and concentrated sources of carbon dioxide drawn from unavoidable emissions can be used for the synthesis processes.

Figure 12 and Figure 13 portray the costs that would be feasible if CO_2 were sourced from unavoidable process emissions to be used for the synthesis of methane and Fischer-Tropsch products. The comparison of the costs for using CO_2 from direct air capture or DAC (€145 per tonne) with the costs for using CO_2 from industrial point sources (€50 per tonne) indicates that the costs associated with synthetic methane and Fischer-Tropsch products can be reduced by using CO_2 from industrial processes. However, the energy carriers would still end up being much more expensive than their fossil fuel equivalents natural gas and crude oil.

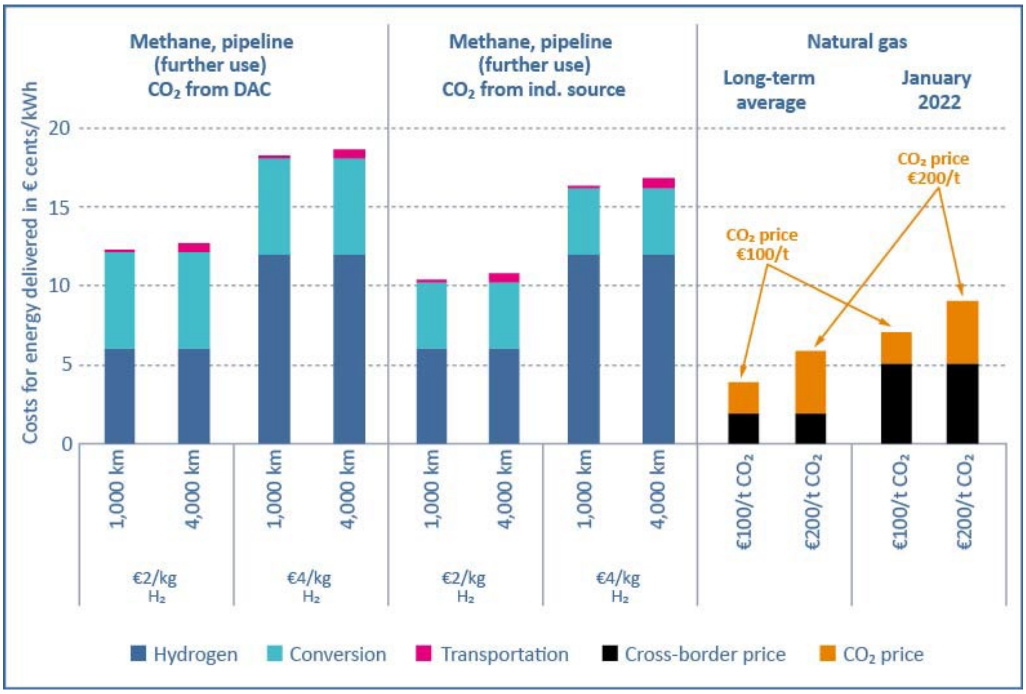


Figure 12: Costs of importing synthetic methane produced using green hydrogen with CO_2 from DAC or industrial point sources, compared against the fossil fuel natural gas. Different distances and green hydrogen production costs are presented to provide different options for the comparison. The costs for CO_2 from DAC are set at €145/tonne and the costs for CO_2 from industrial sources are set at €50/tonne. For the costs of the fossil fuel natural gas, €5,300/TJ (approx. €0.019/kWh) has been applied for the long-term average and €14,100 TJ (approx. €0.051/kWh) has been applied for January 2022.[50] The long-term average equates to the average cross-border prices for natural gas between 2001 and 2020 (not including the CO_2 price). (Source: authors' own calculations and the Federal Office for Economic Affairs and Export Control)

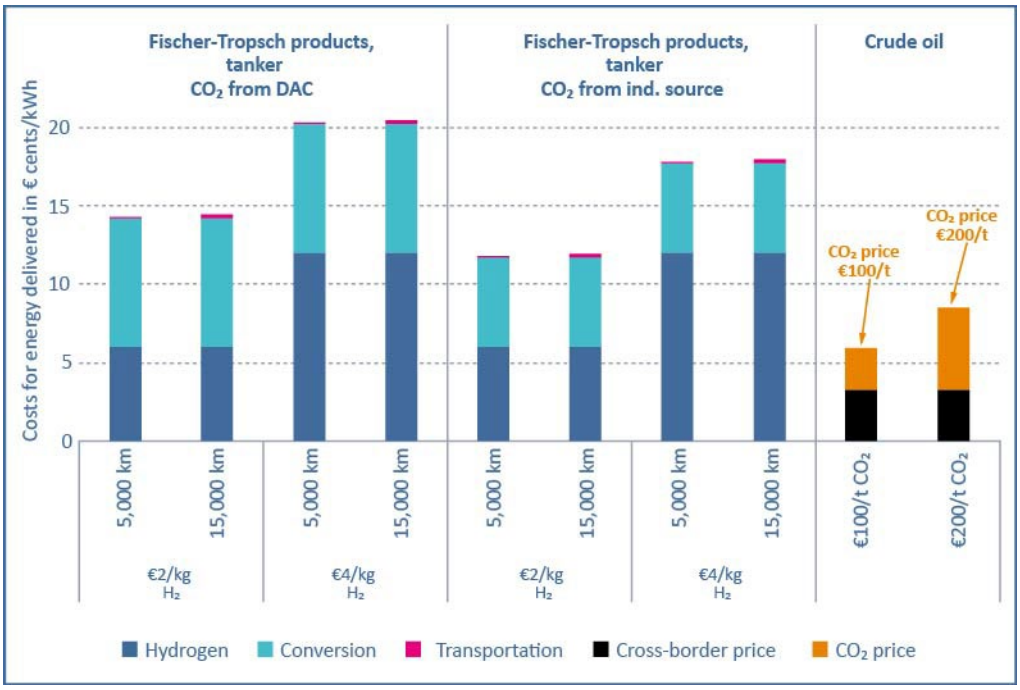


Figure 13: Costs of importing Fischer-Tropsch products produced using green hydrogen with CO_2 from DAC or industrial point sources, compared against the fossil fuel crude oil. Different distances and hydrogen production costs are presented to provide different options for the comparison. The costs for CO_2 from DAC are set at €145/tonne and the costs for CO_2 from industrial sources are set at €50/tonne. For the costs of the fossil fuel crude oil, €385/tonne (approx. €53/barrel) has been applied.[51] This equates to the average cross-border prices for crude oil between 2001 and 2020 (not including the CO_2 price). (Source: authors' own calculations and the Federal Office for Economic Affairs and Export Control)

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50 Cf. BAFA 2022

51 Cf. BAFA n.d.

4.5.3 Ammonia and methanol

Finally, the costs of producing and importing synthetic **ammonia** and synthetic **methanol** are compared against the costs of their equivalents produced in the conventional way. Much like pure hydrogen, ammonia produced using renewable energy has the potential to be competitive given favourable local conditions and short distances to be covered even when CO_2 prices are low. With methanol, however, it depends much more on how much it costs to produce green hydrogen and what the prices for CO_2 will be at the time (see Figure 14). According to the calculations, synthetic methanol would be competitive even with low CO_2 prices provided that the CO_2 required for the methanol synthesis could come from industrial point sources.

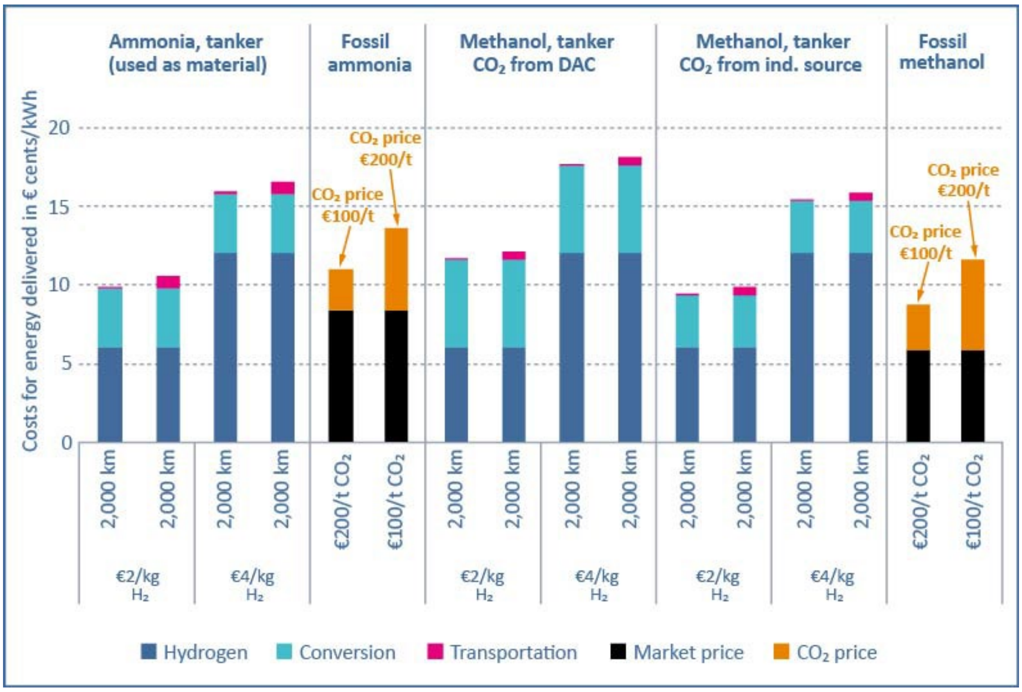

Figure 14: Costs of ammonia and methanol produced using green hydrogen compared against the costs of the comparable fossil energy carriers. Different distances and hydrogen production costs are presented to provide different options for the comparison. The costs for CO_2 from DAC are set at €145/tonne and the costs for CO_2 from industrial sources are set at €50/tonne. For the costs of the fossil-based energy raw materials, €430/tonne has been applied for ammonia[52] and €340/tonne has been applied for methanol[53]. These costs correspond to the average wholesale prices in Europe between 2011 and 2020.[54] (Source: authors' own calculations and Green Markets through Bloomberg and Methanex)

Figure 15 presents a summary of the costs for producing and transporting all the energy carriers discussed in this section given different costs for hydrogen production and a variable CO_2 price. The various costs associated with preparation for transport (compression and liquefication), synthesis of energy carriers, auxiliary materials (carbon and nitrogen) and potential conversion losses are collated under "Preparation and transportation" in this diagram. The costs for importing hydrogen are made up of the

52 Average of wholesale prices in Western Europe between 2011 and 2020 (cf. Elten et al. 2021).

53 Average of wholesale prices in Europe between 2011 and 2020 (cf. Methanex 2022).

54 The CO_2 price set by the EU Emissions Trading System (EU ETS) is already included in the wholesale prices. However, the average certificate price within the EU ETS was only around €10 between 2011 and 2020.

production costs (blue) and the costs for preparation and transportation (magenta). Orange represents the different surcharges for the greenhouse gas emissions, corresponding to the CO_2 price.

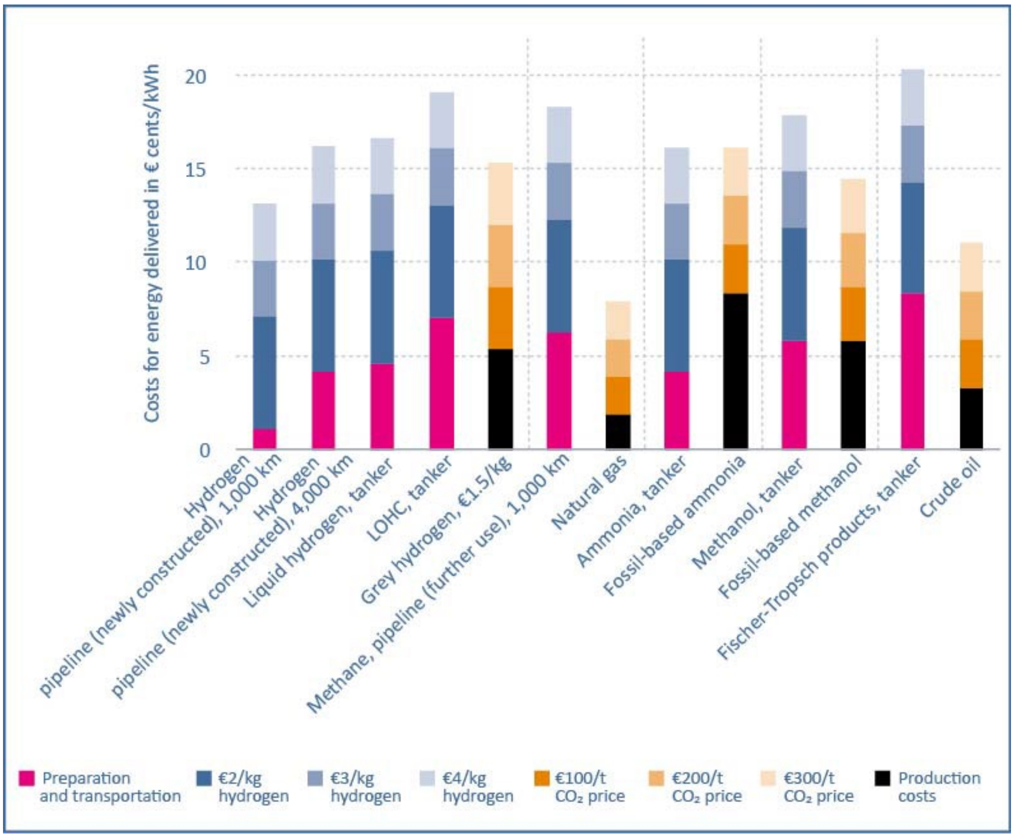

Figure 15: Comparison of the costs of synthetic energy carriers compared against the fossil fuel equivalents. The costs vary on the basis of different hydrogen production prices and different CO_2 prices associated with fossil energy carriers. The costs applied for fossil energy carriers correspond to the costs used in Figure 11 to Figure 14 (source: authors' own calculations).

4.6 Key factors influencing the modelling calculations

Many different assumptions and pieces of input data feed into the results of the modelling calculations. Some of these influencing factors have already been discussed, including the hydrogen production costs, the distance to be covered, the costs of obtaining CO_2, and rising natural gas prices. The following parameters and assumptions also impact heavily on the results:

- The **electricity costs** influence the costs of hydrogen above all else, but they also have a knock-on effect on the costs of hydrogen liquefication, synthesis and, where applicable, hydrogenation, which is the process used to extract hydrogen from the hydrogen carriers.
- The **capacity** at which the systems (electrolysis systems, liquefiers, synthesis systems, pipelines) are used can also have a significant impact on the cost structure. It is important that systems are used at a high capacity in any situations where the investment costs are very high. In this context, the utilisation behaves in the opposite to the electricity costs: The minimum useful

capacity equates to the full-load hours of electricity generation. As the utilisation rate is increased beyond that point, electricity generated from wind and solar power becomes increasingly expensive because there will be more generation peaks that cannot be used or that will necessitate temporary storage so that the renewable energy can be used at a later stage when not so much energy is being generated, which will incur additional costs. It is necessary to strike the right balance between the costs of the electricity supply and the costs of using the systems at a lower rate. This has been roughly estimated in the calculations (further details can be found in the reference material[55]).

- The **imputed interest rate** and the **depreciation period** influence the costs of all capital-heavy aspects of the transport options (and any elements that come earlier and later in the chain). For example, if the interest rate of 8% used for the modelling calculations is reduced to 6%, the annuity is reduced, which means that the annual capital costs decrease by around 14% with a depreciation period of 20 years. Similarly, these capital costs increase by 15% if the interest rate is increased to 10%.

It is important to reiterate at this point that the calculations in this analysis paper have been performed for the **year 2030**. Long-term technological developments may well alter the costs of specific energy carriers and the energy efficiency levels of the transport options in relation to one another.

Deep dive: What is more cost-effective: synthesis in Germany or importing synthesis products?

In principle, synthesis products such as ammonia, methanol and Fischer-Tropsch products can be synthesised from green hydrogen **in the location where the hydrogen is produced** or the green hydrogen can be transported to Germany for **the synthesis process to take place in Germany**. The modelling calculations do not provide a conclusive answer as to which of these options is more cost-effective. There are factors and arguments in favour of both alternatives. A final conclusion would require an in-depth assessment of the entire production chain, factoring in the various local conditions (including salary costs and the existence of relevant infrastructures) and integrated processes that are of major importance within the chemical industry in particular.

However, the calculations performed here do provide some insight into the factors that would be critical for that assessment. In the case of **ammonia**, for example, it is almost always more cost-effective to import it after it has been synthesised. But if it is possible to integrate ammonia synthesis with other processes using existing systems in integrated chemical parks and meet more of the demand in the process, it may be worth performing the synthesis directly on site. Access to hydrogen that had been cost-effectively imported[56] or produced domestically would be essential in this case, though. In the case of **methanol**, synthesis in Germany only makes financial sense when a cost-effective CO_2 point source is available domestically (from industrial processes, for example). In this scenario, it may even be more cost-effective to create new systems to obtain CO_2 and perform methanol synthesis in Germany than it would be to import methanol produced using CO_2 obtained from air separation (DAC).

55 Cf. Schmidt et al. 2022.
56 Imported via a large pipeline from elsewhere in Europe or Northern Africa at the furthest.

5 Qualitative comparison of the transport options

In order to provide a full assessment of the options for transporting hydrogen and determine whether or not they can be implemented quickly, other factors need to be considered beyond the costs and energy efficiency levels presented through the calculations (see Section 4). These more qualitative aspects include considerations as to whether any existing infrastructures can be drawn upon for transportation purposes and whether any regulatory or political obstacles are standing in the way of establishing global supply chains. It is also important to assess any particular safety or environmental risks associated with transporting the energy carriers. As a way of introducing these additional aspects to the assessment of the transport options, the working group developed the list of criteria outlined in this section. When considering the findings of the analysis in this paper, it is important to remember that unforeseen dynamic developments, such as the much stronger focus on LNG deliveries from abroad in the wake of Russia's invasion of Ukraine, can change the basic assumptions upon which the assessment has been made.

5.1 Assessment criteria

The working group set out the following **additional criteria** to allow for a broader assessment of the various transport options:

1. **Anticipated implementation time:** How long can it be expected to take to move from the contract being concluded to the first commercial delivery being made? This factor focuses on the transportation of energy carriers and is assessed separately from the availability of (green) hydrogen. Technical, planning and organisational aspects are all considered.
2. **Existing import infrastructures:** Are there already any infrastructures in place that can be used to import energy carriers into Germany? If there are no import infrastructures already in place in Germany, are there any infrastructures within Europe that could be used for transportation to Germany in the foreseeable future?
3. **Political and regulatory framework:** How much effort will be required to create the political and regulatory framework conditions required for the transport options to be implemented? How likely is it that the anticipated changes to the regulatory framework will be made by 2030?
4. **Path dependencies and lock-in effects:** Would a strong focus on one transport option involve the risk of exacerbating existing dependencies or

creating new dependencies? Unwanted dependencies can come in different forms: geopolitical (e.g. dependency on individual export countries), infrastructural (e.g. geographic dependency based on an existing pipelines), financial (e.g. decisions forced due to investments made, danger of stranded assets) and energy-related (e.g. narrow focus on specific energy carriers).

5. **Energy system stability:** Can the energy carriers under consideration be flexibly integrated into the energy system by 2030? Will they help improve the security of supply within the system as a whole in Germany and Europe, for example at times when there is little wind and solar power to draw on.
6. **Environmental impact:** Are the risks minimal for the environment, flora and fauna in the event of leaks and accidents? How toxic are the energy carriers being considered?
7. **Safety:** How high are the risks for people who deal directly with the transport medium or are not directly involved? What are the chances for damages at material assets like of buildings and technical equipment? How unlikely is it that accidents causing serious damage will occur?

The assessment is based on a **five-point rating scale**. Double minus (--) is at the bottom of the scale, while double plus (++) is at the top of the scale. For example, a double minus rating under import infrastructures would mean that there are no existing infrastructures in place. The same rating for environmental impact would mean that the transport medium is highly toxic and poses a serious threat. A detailed description of all of the assessment criteria and the rating scale can be found in the reference material.[57]

This up-to-date assessment is based on the judgement of the members of the working group “Hydrogen Economy 2030” and research conducted using the literature. The results have been discussed at length within the working group and validated by input from further experts.

5.2 Results of the qualitative assessment

Table 2 provides an overview of the qualitative assessment of the transport options on the basis of the criteria set out above. It clearly indicates that none of the options scores positively across all the criteria. Instead, each of the options has its own advantages and disadvantages. The sections that follow provide an overview of the main results for the assessment criteria introduced above. The implementation requirements that arise in part from the aspects considered in this section will be discussed in greater depth in Section 8.[58]

57 Schmidt et al. 2022.
58 Cf. Kölling 2021 and IEA 2021a as additional sources.

	Implementation time	Existing import infrastructure	Political/ regulatory framework	Path dependencies/ lock-in effects	Energy system stability	Environmental impact	Safety
Gaseous hydrogen (repurposed pipeline)	+ (3-5 years)	0	+	0	+	++	0
Gaseous hydrogen (new pipeline)	- (8-10 years)	-	0	0	+	++	0
Liquid hydrogen (ship)	- (8-10 years)	--	-	+	+	++	0
Methane (pipeline) CO_2 from industrial processes	++ (0-2 years)	++	++	-	+	0	0
Methane (pipeline) CO_2 from DAC	- (8-10 years)	++	++	-	+	0	0
Ammonia (ship) used as material	++ (0-2 years)	+ to ++	+	0	0	--	-
Ammonia (ship) with H_2 recovery	0 to - (7-9 years)	+	0	0	-	--	-
Methanol (ship) CO_2 from industrial processes	++ (0-2 years)	++	+ to ++	+	0	0	0
Methanol (ship) CO_2 from DAC	- (8-10 years)	++	+ to ++	+	0	0	0
LOHC (ship) with central recovery	- (8-10 years)	0 to +	+	-	-	--	+ to ++
LOHC (ship) with decentralised recovery	- (8-10 years)	0 to +	+	--	0	--	+ to ++
Products of FT synthesis (ship) CO_2 from industrial processes	++ (0-2 years)	++	++	0 to -	+	--	+
Products of FT synthesis (ship) CO_2 from DAC	- (8-10 years)	++	++	0 to -	+	--	+

Table 2: Evaluation of the transport options considered using selected qualitative criteria.

Implementation time

Assessment scale:

-- ≙ > 10 years, - ≙ 8–10 years, 0 ≙ 6–7 years, + ≙ 3–5 years, ++ ≙ 0–2 years

++ If a transport option is to be implemented on a commercial scale, all the elements along the process chain need to be commercially available. This would be possible most quickly – presumably within the next two years – with the synthetic hydrocarbons **methane, methanol** and **Fischer-Tropsch products**, provided that the carbon required for production could be obtained from industrial point sources (which are expected to be unavoidable for the time being), such as cement factories or bioethanol plants. However, these sources would only cover a relatively small share of the carbon required to produce methanol and products of Fischer-Tropsch synthesis. Although they are only viewed as a partial solution for that reason, they would allow for fast market entry due to the fact that they could be accessed quickly.

The situation is similar for producing and importing **ammonia** intended to be used as a material since all the relevant technology is fully developed and could be implemented quickly too.

\+ In principle, all the technology required for **transporting hydrogen by pipeline** is available. Pipelines are large infrastructures that take a long time to set up, however. If existing natural gas pipelines could be repurposed for hydrogen, though, implementation would be expected to take three to five years.

O Although the technologies required to produce and import **ammonia** are available on an industrial scale, the implementation time is extended if the ammonia is not going to be used as a material but the **hydrogen** bound in it **is going to be extracted** instead. This process – cracking – is not fully developed, so it is estimated that a longer period of between seven and nine years is required (0 to -).

\- If carbon from the air is to be used to produce synthetic hydrocarbons (**methane, methanol, Fischer-Tropsch products**), an implementation time of around eight to ten years is expected for imports since the direct air capture technology is not ready for use on an industrial scale.

The **construction of new pipelines for transporting pure hydrogen** is also likely to take eight to ten years because that is the amount of time required for planning, routing and installing new pipelines. When it comes to **transporting liquid hydrogen by ship**, there is insufficient tanker capacity for the transportation and a lack of landing infrastructures. The work required to rectify both situations is estimated to take around eight to ten years.

Until all technical components are marketable and available on an industrial scale, **hydrogen absorbed by LOHC** is a transport option that is about eight to ten years away from implementation. There is still much work to be done on development and infrastructures for dehydrogenation and recirculation.

Existing import infrastructures

Assessment scale:

-- ≙ nothing already in place, ++ ≙ everything already in place

++ It would be possible to import synthetic **methane, methanol** and **Fischer-Tropsch products** by repurposing existing infrastructures that have previously been used to transport fossil energy carriers without the need to make any major adjustments.

\+ For **ammonia**, the existing infrastructures used to import ammonia produced in the conventional way could be used. In order to fully meet all the current demand for green ammonia in Germany through imports, however, the infrastructures for importing ammonia would need to be expanded. As it stands, only around 22% of the ammonia required in Germany is imported and around three quarters of what is required is produced on the site where it is needed using natural gas and nitrogen from air separation equipment.[59] If the hydrogen is to be extracted from the ammonia, the necessary dehydrogenation systems (crackers) would also need to be developed and set up.

o With some technical input, existing natural gas pipelines could be repurposed for **transporting hydrogen**.

It would appear that the infrastructures already in place for diesel fuels could be used to import **LOHC** after some adaptation. The dehydrogenation systems required to recover the hydrogen are not available at all yet, however. If the hydrogen is to be separated from the carrier material at the location where it is going to be used rather than being separated centrally upon arrival, the carrier material would have to be returned using further infrastructures. These do not exist yet and it is not clear to what extent, if at all, existing infrastructures (including petrol stations) could be suitable for this purpose.

\- There are no larger **pipelines for transporting pure hydrogen** as it stands, but routes already in place for natural gas pipelines could potentially be used to construct new hydrogen pipelines. This alternative would significantly reduce the amount of work required to implement the transport option in terms of the stages from route planning to installation.

-- There are no existing infrastructures for importing **liquid hydrogen by ship**. Fleets of ships and landing terminals at ports would therefore need to be developed and put in place before this option could be implemented.

59 Cf. Destatis 2022a and Destatis 2022b.

Political and regulatory framework

Assessment scale:

-- ≙ implementation unlikely and a great deal of effort involved

++ ≙ implementation likely and little effort involved

++ There are already regulations in place for synthetic **methane** and **products of Fischer-Tropsch synthesis** and they would continue to apply.

\+ With some limitations, the same also applies to synthetic **methanol** for use as a fuel additive and chemical raw material as well as to **ammonia**, which is already heavily regulated when used as a chemical raw material. However, there is no existing regulatory framework for either or for **LOHC** when they are used as energy carriers. It would be possible to build on the existing legal foundation in all three cases, though. LOHC and diesel fuel could be compared for this purpose.

o Regulations would need to be drawn up for the **recovery of hydrogen from ammonia**, with this the option is receiving a slightly worse rating than ammonia being used as a material.

Newly constructed pipelines for **gaseous hydrogen** would require extensive planning and approval processes, which would have to include route identification and planning. This would not be necessary in the event that existing natural gas pipelines were repurposed for hydrogen (hence the slightly higher rating), but there would still be a need to quickly clarify unanswered questions relating to regulations for hydrogen transportation networks to make it possible for investment decisions to be made in a timely manner. One of these questions would concern the format of a new operating licence that would be required after a natural gas pipeline has been repurposed for hydrogen.

\- The specific regulatory framework surrounding the transportation of **liquid hydrogen** by ship is virtually non-existent.

Path dependencies and lock-in effects

Assessment scale:

-- ≙ high risk, ++ ≙ no risk

+ The risks of long-term path dependencies are lowest for the options of importing **liquid hydrogen** and **methanol** since both of them can be used for a wide range of applications and the fact that they are transported by ship means there is no risk of being geographically tied to individual countries of origin.

o **Gaseous hydrogen** is very versatile in its potential usage, but the installation of a pipeline results in a geographical restriction.

If Fischer-Tropsch products are to be imported on an industrial scale, it is important that there is enough incentive for buyers to switch to alternative energy carriers promptly if possible. Otherwise, there is a risk of delaying essential transformation processes. The development and spread of alternative technologies (like e-mobility technology) could be delayed by people being reluctant to make changes because they expect nothing to change for them as the end users as a result of the simple switch from fossil-based to synthetic hydrocarbons. This could introduce the risk of the current dependency on hydrocarbon-based liquid energy carriers on the road and rail, and in the heating market, being prolonged by the widespread use of products of Fischer-Tropsch synthesis.

Ammonia that is intended to be used directly as a raw material in industrial applications does not involve any risk of creating new path dependencies or exacerbating existing ones because it can be used as an energy carrier as well as a chemical. The use of existing infrastructures does not involve any risk of lock-ins. As far as **ammonia** as a hydrogen carrier medium is concerned, however, the development of infrastructures has the potential to result in lock-ins because there is no scope for them to be used for any other purpose. As the extracted hydrogen can be used flexibly, however, there is not much risk of strong path dependencies being formed on the whole.

\- Importing synthetic **methane** does also pose the risk of users not embracing the necessary transformation and continuing to use the fossil fuel natural gas.

The option of importing **LOHC** requires the creation of a new transportation infrastructure and recovery system. This could result in being tied to this technology in the long term and indeed the transportation capacity for the essential return of the carrier medium. Despite the fact that the hydrogen can be used flexibly once it has been extracted, new path dependencies are likely with this option. High volumes of investment are also required in the carrier materials initially and in their ongoing preparation to ensure that they can be used for the maximum number of cycles.

Energy system stability

Assessment scale:

-- ≙ major negative impact on other key aspects of the energy system
[and] negative impact on the security of supply

++ ≙ major positive impact on other key aspects of the energy system
[and] positive impact on the security of supply

+ Synthetic **methane** can be flexibly integrated into gas turbines and peak load power plants to cover times when there is not enough power from renewable energy sources. The same applies to **pure hydrogen** as long as the plants are "H_2-ready", meaning they are set up to be operated with hydrogen directly.[60] **Fischer-Tropsch products** also have the flexibility to be used in a number of different ways.

o It is likely that **ammonia** used as a material will not be used to produce electricity in Europe[61], meaning it will not have any significant impact on the stability of the energy system. The same applies to **methanol**, which is not expected to be used as an energy carrier to any greater extent.

Where the hydrogen recovery is not central, **LOHC** cannot be incorporated into the energy system on a large scale. If the dehydrogenation of hydrogen is not concentrated in space or time, there is no intermittent high load in this case as there is with central dehydrogenation.

\- **LOHC and ammonia** from which the hydrogen is going to be extracted could impact negatively on the flexibility within the energy system. In the case of central dehydrogenation, the high temperatures required to recover hydrogen (900 degrees Celsius for ammonia and 300 degrees Celsius for LOHC) could exhaust the potential of waste/process heat sources available locally in the future and cause peaks in the demand for energy at the corresponding locations.

60 The first gas turbines from Kawasaki Heavy Industries that have the option of being operated with hydrogen are already being tested (Energate 2021).

61 It is certainly possible that ammonia could be used to produce electricity, with concepts being developed in Japan to bring ammonia into the power supply for coal-fired power plants (cf. Kölling 2021). The roadmap for ammonia also suggests a significant increase in its usage to produce electricity and as a fuel for ships' engines (cf. IEA 2021a). The working group is of the opinion, however, that it is unlikely that ammonia will be used to produce electricity on a large scale in Europe – largely down to safety concerns that apply to anyone handling it.

Environmental impact

Assessment scale:

-- ≙ high potential to damage the environment, ++ ≙ no risk of damaging the environment

++ The transportation of pure **hydrogen** is associated with virtually no environmental risks because it dissipates quickly in the event of leaks and any hydrogen that is unintentionally released only has a minimal, indirect greenhouse gas effect[62].

o **Methanol** poses a slight risk of water pollution. Thanks to its biodegradability and water solubility, however, it is soon diluted in bodies of water, meaning it is associated with short-term damage to organisms rather than causing harmful effects in the long term.

With **methane**, the biggest environmental concern relates more to its highly damaging impact as a greenhouse gas rather than any immediate damage it can cause to the environment.

-- The chemical and physical properties of **ammonia, LOHC** and **products of Fischer-Tropsch synthesis** mean that these substances have the biggest potential to cause damage in the event of an incident.

In the case of **products of Fischer-Tropsch synthesis,** the risks are similar to those currently associated with the fossil fuel crude oil. Incidents at sea or leaks in pipelines, for example, would have a serious, long-lasting impact on flora and fauna in the ocean.

LOHC is hazardous to water when unloaded and behaves similarly to diesel when loaded with hydrogen, meaning the long-term impact on the environment would be similar to an oil spill in the event of a leak.

Ammonia is reactive and highly toxic in water. A great deal of immediate environmental damage could be caused locally in the event of an incident, especially in areas where the flow of water is not so steady like ports and inland waterways.

62 Cf. ESKP n.d.

Safety

Assessment scale:

-- ≙ high risk, ++ ≙ no risk

- \+ The transport options with the least potential for danger are **LOHC** and **products of Fischer-Tropsch synthesis**. Liquid hydrocarbons and LOHC, which behave similarly to diesel when they have absorbed hydrogen, are very safe and straightforward to handle since they are inert and non-explosive.
- o **Pure hydrogen** has more potential for danger by comparison (due to the risk of explosion) as do **methane** (due to the risk of fire and explosion) and **methanol** (which is highly flammable and toxic).[63] Strict safety standards must be followed when handling gases like compressed hydrogen – especially in enclosed spaces and buildings in close proximity to other buildings.
- \- **Ammonia** has the biggest potential for danger since it is a reactive, explosive and corrosive substance. In the event of accidents, it can harm people nearby and damage property like port infrastructures, buildings and technical equipment. Stringent safety requirements must be followed along the entire transport chain because ammonia is so reactive.

63 Cf. Methanex 2020.

6 Interim summary

The modelling calculations (Section 4) and the qualitative analysis (Section 5) have demonstrated that each transport option has its own advantages and disadvantages. The particular priorities for properties, uses and availability will determine which energy carriers would be most advantageous as an import solution. To summarise, the following conclusions can be drawn from the analysis:

1. **Renewable ammonia and synthetic hydrocarbons would be available quickly.**

The option of **importing ammonia** produced using green hydrogen and transported by ship could be competitive with ammonia produced in the conventional way within the space of just a few years. With production costs of under €3 per kilogram of hydrogen, this option would be competitive even with low CO_2 prices of around €100 per tonne. The implementation time for this option would be short since the production technology and the infrastructures required for transporting ammonia are already available and their usage is common standard. If ammonia was to be imported in larger volumes, however, the existing import infrastructures would need to be extended since only around 22% of the ammonia required in Germany is imported as it stands.

Renewable ammonia could provide a direct replacement for conventional ammonia and be used as a raw material in the production of nitrogen-based compounds like urea and fertilisers. If the 3 million tonnes of ammonia used in Germany every year[64] were replaced with renewable ammonia, CO_2 emissions could be reduced by around 4.5 million tonnes annually[65] and 900,000 tonnes of natural gas could be saved in that time too[66]. Even if the transportation of renewable ammonia to Germany was not climate-neutral to start with and involved tankers fuelled by heavy fuel oil travelling over 10,000 kilometres, the reduction in CO_2 emissions stipulated above would only drop by less than 3%. This is because 1 tonne of ammonia produced in Germany using grey hydrogen causes around 1.8 tonnes of CO_2 emissions. Meanwhile, 1 tonne of renewable

64 Cf. VCI 2021.
65 For every tonne of ammonia, around 1.8 tonnes of CO_2 are emitted (cf. Agora Energiewende 2020).
66 Around two thirds of the ammonia produced in Germany is based on natural gas. Between 0.4 and 0.5 tonnes of natural gas is required for every tonne of ammonia (cf. Fraunhofer ISI 2013). That equates to around 11 terawatt hours of natural gas.

ammonia transported over 10,000 kilometres to Germany only causes around 50 kg of CO_2 emissions (due to the heavy fuel oil used for the tankers).

One major disadvantage of transporting ammonia is that it is highly toxic. In the event of an accident, serious damage could be caused to the environment, while people nearby could suffer from severe poisoning. That is why the safety requirements are so high for the transportation of ammonia.

It would also be quick to start producing and **importing synthetic hydrocarbons** (methane, methanol and Fischer-Tropsch products) if the carbon could be sourced from unavoidable industrial point sources, such as at cement factories. Synthetically produced **methanol** could provide a financially attractive alternative to methanol produced in the conventional way within just a few years with CO_2 prices of around €200 per tonne. Conversely, synthetic methane and Fischer-Tropsch products are expected to remain much more expensive than their equivalents made from fossil energy carriers.

Synthetic hydrocarbons could provide a direct replacement for natural gas, conventional methanol and crude oil. However, the volume of hydrocarbons that could be produced using CO_2 from industrial processes is limited. The cement industry in Germany was responsible for around 20 million tonnes of CO_2 emissions in 2017, for example, with 65% of those emissions being linked to processes.[67] Even if it were possible to use all the CO_2 released by processes to synthesise hydrocarbons, only around 66 terawatt hours of synthetic methane could be produced. That would equate to around 7% of the natural gas used in Germany each year (correct as at 2021).[68] Alternatively, it could be used to produce around 14.5 million tonnes[69] of methanol, which would cover the 1.5 million tonnes of methanol produced in Germany every year about ten times over.[70]

It is important to remember that hydrocarbons produced using CO_2 from industrial point sources are **not climate-neutral**. This is because the CO_2 that was previously contained, for example in limestone used to produce cement, does ultimately end up being released into the atmosphere upon combustion of the hydrocarbons. With that in mind, the production of synthetic hydrocarbons would need to gradually be transitioned so that sustainable sources of CO_2 were used (such as DAC). This kind of transition would need to be clearly regulated from the outset to avoid any fossil fuel lock-in effects.

67 Cf. Agora Energiewende 2020.
68 Cf. BDEW 2019.
69 With 1.375 kilograms of CO_2 required for every kilogram of methanol.
70 In the year 2020, 1.523 million tonnes of methanol were produced in Germany (cf. VCI 2021).

2. **Hydrogen pipelines are the most cost-effective way of transporting pure hydrogen that would be feasible within the space of a few years.**

Looking at the costs, the transportation of **pure hydrogen by pipeline** over a distance of up to 4,000 kilometres is the most cost-effective option. This option becomes even more cost-effective when existing natural gas pipelines can be repurposed for the transportation of pure hydrogen. Transporting hydrogen by pipeline is also the **most efficient** of all the transport options considered. Taking into account the amount of energy used (in the form of renewable electricity) in the country where hydrogen is produced, this transport option would allow for the largest amount of energy to be used in Germany when compared against all the alternatives considered in this analysis paper (see Table 1). This can be important because space with favourable conditions for producing renewable energy is limited and yet the demand for synthetic energy carriers is set to increase significantly all around the world (see Section 2.1). There are other arguments in favour of transporting hydrogen by pipeline: Pure hydrogen is versatile in its usage and it is not toxic. When handled properly, the safety risks are minimal. Given that the costs of transportation by pipeline increase as the distance to be covered increases, this option is ideal for **importing hydrogen from other European countries or countries neighbouring the EU**.

If work to repurpose an existing pipeline or construct a new pipeline was started today, it could potentially be possible to be transporting a significant volume of hydrogen to Germany within around 3 to 5 years (repurposing) or 8 to 10 years (new construction) provided that planning and implementation were efficient and the capacity of renewable energy systems in the country of origin was built upon as required at the same time (see Section 5.2). It must also be considered, however, that large volumes of renewable electricity would have to be provided in the exporting country to ensure the cost-effective operation of the pipelines. With a pipeline with a diameter of 1,016 millimetres and the capacity to transport around 6,000 to 7,000 tonnes of hydrogen every day, around 50 terawatt hours of hydrogen could be transported to Germany every year.[71] But the production of the hydrogen would require around 85 terawatt hours of electricity in the exporting country, which would equate to a combined wind power and photovoltaic system output of around 35 gigawatts.[72] To put this into context, that equates to almost the entire capacity of wind and photovoltaic systems that were installed in Spain in 2020 (approximately 40 gigawatts).[73] Even a small pipeline with the capacity to transport around 5 terawatt hours of

71 The pipeline has been assumed to be used at around 60% of its full capacity to account for a volatile feed-in from the systems supplying the renewable energy. Full capacity would mean that storage facilities would also be required in the exporting country, which would increase the costs.

72 With an average of 2,500 full-load hours assumed for the renewable energy systems. Some of the energy produced would have to be curtailed (around 10%) to ensure the most cost-effective set-up.

73 Cf. IRENA 2021.

hydrogen each year would need around 10 terawatt hours of electricity, equating to a renewable energy system capacity output of around 4 gigawatts in the exporting country.

3. Transporting hydrogen by ship is a crucial option in the long term.

The transportation of **liquid hydrogen by ship** is a valid option for importing hydrogen from countries that are further away (outside of Europe), which could also help to diversify hydrogen imports. Importing hydrogen in this way makes most economic sense when the distance to be covered exceeds 4,000 kilometres because the major benefit of transportation by ship is that the distance has very little impact on the overall costs associated with hydrogen imports. In an extreme example where hydrogen is being transported to Germany from Australia (around 20,000 kilometres away) rather than Morocco (around 2,700 kilometres away) and the production costs are the same, the overall costs will only increase by around 10%.

The problem here is that the liquid hydrogen tankers required to make this a feasible transport option are still being developed. In a world first in spring 2022, a tanker transported liquid hydrogen at a temperature of -253 degrees Celsius from Australia to Japan. The plan for this Australia/Japan project is that the partnership will be able to shift from a successful pilot phase to a commercial phase in 2030.[74] The manufacturer Kawasaki is also intending to be able to offer large liquid hydrogen tankers on a commercial basis in 2030.[75] However, it is impossible to predict at this stage whether these timescales are feasible or how long it will be before fleets of ships with the required capacity will be available for the commercial transportation of liquid hydrogen. It is also true that the regulatory framework conditions for importing liquid hydrogen by ship need to be drawn up by that point.

In principle, hydrogen could also be absorbed by a **carrier medium** like **LOHC or ammonia**, which could then be dehydrogenated after transportation to Germany. From a cost perspective, though, these alternatives are not as favourable as transportation in liquid hydrogen tankers. Both technologies still also need considerable development and scaling, which draws out the timescale. Moreover, there are much higher environmental risks associated with transporting LOHC and ammonia than with transporting pure hydrogen.

74 Cf. HESC 2022 and HySTOC 2019.
75 Cf. Kawasaki 2019.

4. Importing green hydrogen products is a sensible move between now and 2030 as far as the climate protection is concerned.

Fewer CO_2 emissions are associated with the production and transportation of green hydrogen and its synthesis products than with the fossil fuels being relied on currently. Looking at the **CO_2 emissions**, it would make sense even now to import green hydrogen by pipeline and even by ship from countries with favourable local conditions for producing hydrogen – even though the ships would be fuelled by heavy fuel oil.

It was not possible to investigate the CO_2 emissions linked to the imported products in enough depth for the purposes of this analysis paper (see the introduction to Section 4). However, initial rough calculations performed as part of the analysis suggest that CO_2 emissions could be reduced significantly by importing green hydrogen products. For example, 1 kilogram of hydrogen produced from natural gas as normal results in around 10 kilograms of CO_2 emissions. But 1 kilogram of green hydrogen transported over 10,000 kilometres to Germany on a liquid hydrogen tanker fuelled by heavy fuel oil would only be associated with about 0.7 kilograms of CO_2.[76] Significant reductions in CO_2 can also be made with the transport options that can play an important part in meeting the demand for green hydrogen and its synthesis products by 2030 (see above):

- If the volume of **ammonia** currently imported into Germany is to be replaced with imported renewable ammonia, that would amount to around 460,000 (2011) to over 700,000 tonnes (2015) annually[77]. To cover that volume, for example, one or two large tankers would have to be travelling backwards and forwards continuously (ten trips per ship). As a result, CO_2 emissions could be reduced by somewhere between 830,000 and 1.3 million tonnes.
- The German steel industry has set itself the target of making one third of its primary steel production in Germany (around 10 million tonnes of steel) almost or entirely free from CO_2 by 2030.[78] If this is to be achieved entirely using green hydrogen, 19 terawatt hours of **hydrogen** will be required. That is the same as one third of the yearly capacity of a large pipeline. Green hydrogen could save 17 million tonnes of CO_2 in this case.
- In order to replace the fossil-based **methanol** being imported currently (around 1.3 to 1.5 million tonnes gross per year)[79], two to four tanker ships would need to travel back and forth throughout the year to transport green

76 In both cases, the CO_2 emissions associated with the upstream chains have not been taken into account.

77 The (gross) import volumes fluctuated quite considerably within the specified range over the past ten years. That fluctuation was even more marked for net imports, ranging between 100,000 tonnes (2011) and 440,000 tonnes (2015). IVA 2020.

78 Cf. BMWi/WV Stahl/IG Metall 2021, page 1 and WV Stahl 2022.

79 World Bank 2022.

methanol to Germany. This would reduce the CO_2 emissions by between 1.1 and 1.6 million tonnes.

- **Products of Fischer-Tropsch synthesis** can be used in the aviation sector and elsewhere. According to the PtL Roadmap set out by the German Federal Government, synthetic kerosene is to replace at least 2% of the kerosene distributed in Germany by 2030.[80] Between 1 and 1.5 tanker loads each year would be enough to import this volume. The high carbon content in Fischer-Tropsch products would mean that CO_2 emissions could be reduced by around 1.1 to 1.5 million tonnes provided that those products are climate-neutral.

5. A great deal of development work is still required on synthetic hydrocarbons produced using non-industrial sources of carbon.

Looking to the long term (over ten years into the future), importing **synthetic hydrocarbons** produced on the basis of green hydrogen and CO_2 captured from the air may prove sensible and necessary as a way of replacing fossil energy carriers and achieving the transition to a climate-neutral energy supply. But, as it stands, much **development and scaling** is required for extracting CO_2 through direct air capture (DAC) in order to reduce the process costs.

Importing synthetic methane and products of Fischer-Tropsch synthesis will still be much more expensive than importing natural gas and crude oil going into the year 2030 – even with CO_2 at a high price. Methanol is an exception here since it could prove to be more favourable than methanol produced in the conventional way in the year 2030 if CO_2 emissions would be priced at around €200 per tonne.

Importing the products of Fischer-Tropsch synthesis could still be a sensible option if they are intended to be used for specific purposes due to their properties, such as in aviation, or if existing distribution networks and storage facilities are intended to be used. The same applies to methane produced synthetically. After all, there are already infrastructures and regulations in place for importing and distributing it, so the existing technology can be drawn upon directly.

There is, however, a risk that the use of fossil energy carriers will be prolonged in the long term if a gradual replacement with synthetic energy carriers is planned at this stage but does not turn out to be financially viable. The environmental risks associated with Fischer-Tropsch products also present another disadvantage. In the event of an accident, they would be similar to the risks associated with crude oil and the danger of methane slip with serious greenhouse gas potential in the short to medium term in relation to the production and transportation of synthetic methane.

80 Cf. German Federal Government 2021, page 5.

7 Analysis of the export potential of selected countries based on exemplary transport options

The analysis of the various transport options in Sections 4 and 5 allows for a general comparison to be made so that the advantages and disadvantages of those transport options and their potential contribution towards meeting the growing demand for hydrogen in Germany can be evaluated. Before specific transport routes can be assessed further, the results of the general comparison of the various options need to be connected to country-specific details and presented in a wider context. This additional information on specific countries (see Section 7.2) makes it possible to make general assessments on particular options that look favourable at first glance and either confirm that initial impression or elaborate on it, with a view to also putting the options that appear less favourable into perspective. Linking the analysis of the transport options to knowledge about individual countries provides a practicable insight into the bigger picture, which in turn makes it possible to draw conclusions as to whether options for importing hydrogen are feasible in the short to medium term.

7.1 Country analysis methodology developed to provide an overview and allow for comparison

7.1.1 Methodology

The working group developed a succinct list of criteria that covers all the key aspects so that they could present the options convincingly in a wider context without making the process overly complex and impractical. Combined with underlying indicators, this methodology provides an overview of the renewable energy potential of each of the countries considered, which is important because favourable conditions for producing renewable energy are an essential requirement for any country producing green hydrogen locally. The list of criteria also covers the production and export infrastructures that are already in place or need to be established in the countries being investigated. Opportunities for German companies to operate there are considered too. The analysis also incorporates the relevant economic, political and social framework conditions for producing and exporting hydrogen and its synthesis products.

The countries are analysed on the basis of these eight criteria:

1. conditions for producing renewable electricity
2. sustainability of energy system (based on emissions)
3. technical potential to export hydrogen[81]
4. conditions for transporting hydrogen/PtX products
5. security of investment and supply
6. opportunities for German companies
7. export readiness
8. social acceptance

These criteria are backed up by a more extensive system of indicators (please refer to the reference material[82]). For example, *Export readiness* (7) is based on the following indicators: (a) *Existing energy partnerships* (political network level), (b) *Existing strategies for (green) hydrogen* (political level), (c) *Existing export and international trade infrastructures* (technical/economical level with *sub-indicators* "*Trade volume with mineral oil products*", "*Trade volume with natural gas*" and *"Container throughput"*) and the (d) *Human Development Index*, which also addresses the availability of local specialists who can export green hydrogen (please refer to the reference material for further details[83]). The assessment scheme could also be extended beyond the scope of the criteria and indicators being used. For example, this could be an option in the event that additional information specific to the country or region in question needed to be factored into the analysis. For that reason, combined with the fact that the working group did not want their analysis to be misconstrued as forceful recommendations, the eight criteria were not weighted in any way. On that basis, the methodology presented here for the country analysis is deliberately restricted to making observations and identifying each country's general strengths and weaknesses, which provide the foundation for more in-depth analysis.[84] With a view to enabling readers of this analysis paper to assess additional countries (that have not been considered in the text that follows) with speed and ease, the methodology developed is based largely on the evaluation of information that is available in the public domain, such as through the World Economic Forum, the World Bank and IRENA. Much of the data included in the sources is also updated on a regular basis, ensuring that the methodology for analysing countries remains relevant into the future. This means that older assessments can be updated to reflect the latest information. Analyses of individual countries performed at different points in time can also be presented in chronological order to provide insight into how trends have developed over time.

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81 The "Technical potential to export hydrogen" criterion does draw on findings under two of the other criteria – 1) "Conditions for producing renewable electricity" and 2) "Sustainability of energy system (based on emissions)" – but provides a separate assessment by incorporating further data. This correlation is shown in the radar chart.

82 Cf. Schmidt et al. 2022.

83 Cf. Schmidt et al. 2022.

84 The indicators upon which the criteria are based were not given any weighting either on the understanding that no misleading assessments would be presented (cf. Schmidt et al. 2022). This methodology proved to be robust during a sensitivity analysis.

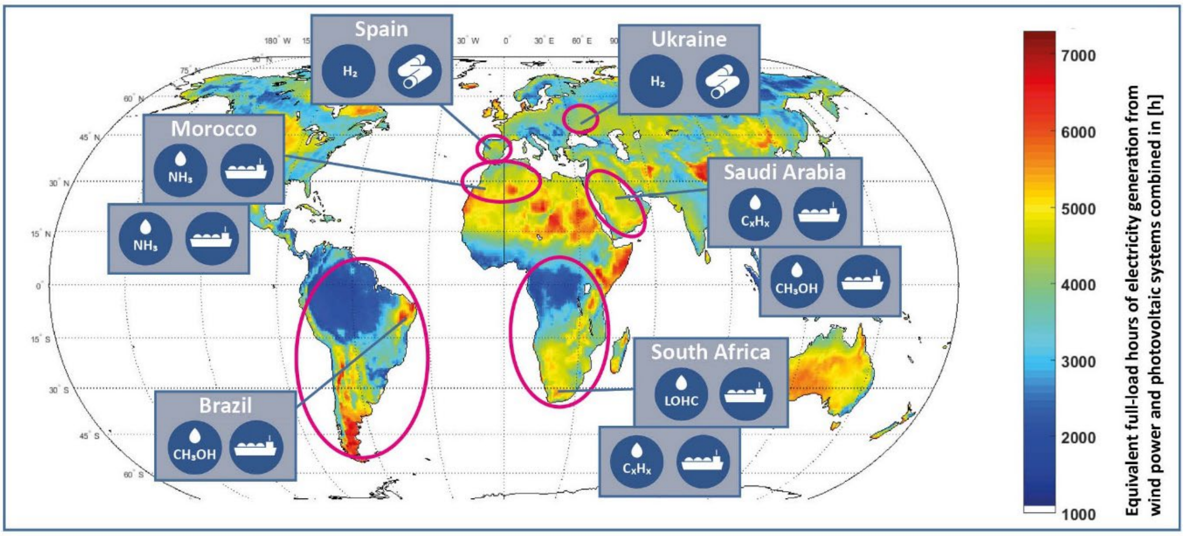

Figure 16: Selected countries/focus regions analysed for hydrogen imports and transport options considered (source: authors' own diagram based on a map from Fasihi/Breyer 2020).

The results of the assessment of the selected potential exporting countries (see Figure 16) on the basis of the criteria were cross-referenced against the prior knowledge of the experts in the working group. This additional step in the process validated the results and added another layer to the assessment of the countries in question. The findings were incorporated into the final rating. For this final rating, each country was given a score on a five-point rating scale ranging from double minus at the bottom to double plus at the top[85] (see Figure 17).

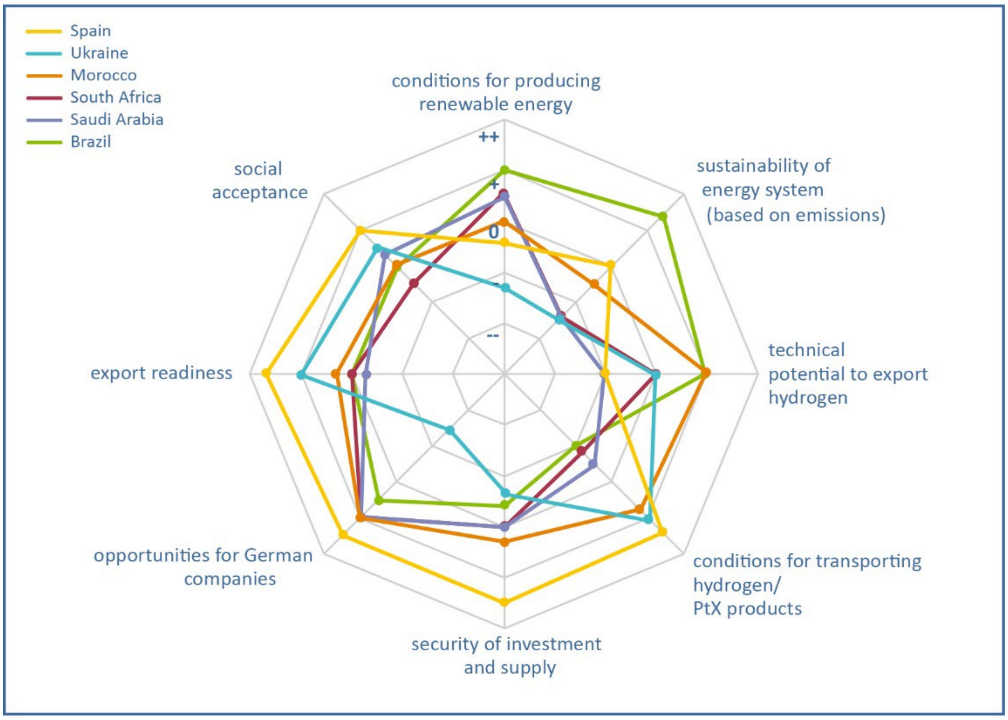

Figure 17: Overview of the results of the country analyses (source: own diagram).

85 Double minus (--) means "unfavourable conditions currently" and double plus (++) means "highly favourable conditions currently".

7.1.2 Selection of countries presented as examples

The countries and focus regions presented in Figure 16 were selected on the basis of their potential for importing green hydrogen to Germany. The choice was made when the working group was first formed – before the initial stages of the analysis were completed. This means that the results of the general analysis of the transport options had no bearing on the countries selected. Furthermore, the selection is not intended to be fully representative of all potential exporting countries. The members of the working group decided on the countries and transport options presented here by way of example with a view to considering a wide range of potential exporting countries and raising the many different points that need to be considered for future partnerships. If these points are incorporated into supply agreements, implemented and developed, they should lead to broad diversification in green hydrogen imports in the medium to long term and in turn help guarantee security of supply.

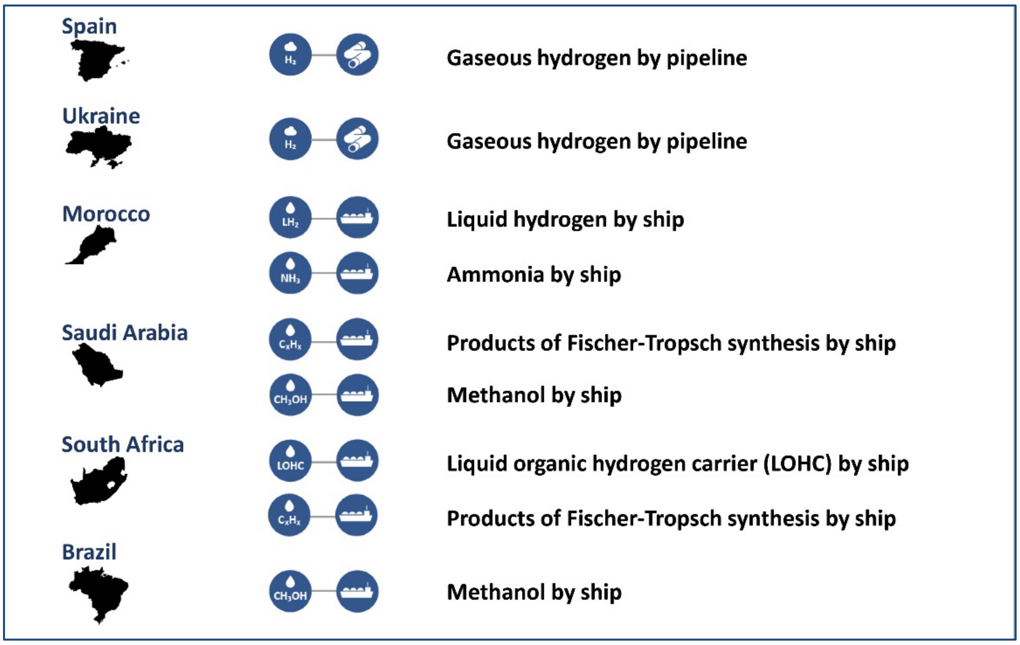

Figure 18: Overview of import routes analysed (source: authors' own diagram).

Looking at the countries selected, **Spain** is representative of a key trade partner for Germany within the European Union that has good solar and wind power potential. **Ukraine** is an Eastern European country that has the special advantage of existing natural gas pipelines with the potential to be repurposed for hydrogen transportation. **Morocco** in Northern Africa represents a country that is outside of Europe but still relatively close to the continent. It also has the benefit of already having an infrastructure in place for ammonia and already partnering with Germany on an industrial level (in relation to energy). **Saudi Arabia** is an example of a country within the Arabian Peninsula with an economy based heavily on exporting fossil energy carriers. Its existing export infrastructures also have the potential to be repurposed for exporting green hydrogen products. **South Africa** was chosen as a country with advanced technology in the energy sector (relating to Fischer-Tropsch synthesis in this case) and as representative of Sub-Saharan Africa. **Brazil** provides some contrast to the other countries considered because it is so much further away from Germany and it faces less of a challenge when it comes to moving away from fossil fuels for its domestic energy supply, with around half of its own end-user energy consumption being covered by renewable energy sources already.[86] Germany has a long tradition of collaborating with Brazil, which also applies to other South American countries like Argentina and Chile. Australia was intentionally ruled out of the analysis because an in-depth study on the feasibility of a hydrogen partnership with Australia is already being provided within the scope of the "HySupply" project acatech and BDI are working on together.

7.1.3 Application focus of the methodology

As a general rule, combining the methodology outlined for the country analysis with the general analysis of the transport options allows for the analysis to be extended to as many exporting countries and transport routes as required. As already mentioned in the introduction, taking specific results and making use of the available analysis tool[87] makes it possible to draw general conclusions as to the potential costs associated with the transportation of hydrogen in different forms (e.g. as pure hydrogen or after methanol synthesis) and on different routes as well as the efficiency of the transport routes (including production, transportation and usage of the hydrogen in Germany)[88] and the framework conditions in the countries of origin that might impact on the feasibility of hydrogen being imported into Germany. On a practical level, the country analysis also reveals obstacles and implementation requirements that will prove relevant when it comes to implementing hydrogen partnerships (see Section 8 for further details). As far as the working group is concerned, the methodology outlined provides a reliable way of performing an initial assessment of routes for importing hydrogen. The working group is not suggesting, however, that this methodology should be taken as an alternative to dedicated location-based assessments that need to be performed in situ when individual projects are being implemented. Before any decisions can be reached about whether to make an investment or go ahead with a project, all the relevant technical, infrastructural (concerning power grids, roads, ports and so on), economic, social and political factors will obviously need to be studied and considered in much more depth. This should take the form of feasibility or sustainability studies (or similar), with the status quo and potential future developments also being factored in.

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86 Cf. IRENA 2018.

87 Further information about the functionality of the tool developed by the working group "Hydrogen Economy 2030" and corresponding notes on its usage can be accessed in the reference material (Schmidt et al. 2022).

88 In the country profiles (see Section 7.2), these details calculated specifically for the countries being considered can be found in the relevant cost comparison chart and in the corresponding diagram depicting the efficiency of the value chain.

It is important to reiterate at this point that the short country profiles that follow represent an assessment of potential export countries from the point of view of Germany. The profiles draw attention to points to be considered before initiating and developing partnerships between nations. Time and workload constraints ruled out the possibility of the working group considering specific stakeholders based in each of the countries as part of this analysis paper. However, this should be viewed as an essential step in successfully establishing partnerships that benefit both trade partners in equal measure (see Section 8 for further details).

7.2 Country profiles

7.2.1 Gaseous hydrogen by pipeline from Spain, representing the Iberian Peninsula

This profile provides an example of transporting compressed hydrogen in gas form via a hydrogen pipeline that does not exist as yet between Spain and Germany. The route would have to be largely created from scratch because there is no existing infrastructure for natural gas with sufficient capacity coming from Spain. This would draw out the implementation time. Based on experience of creating natural gas networks, it can be assumed that this would take at least ten years to implement.

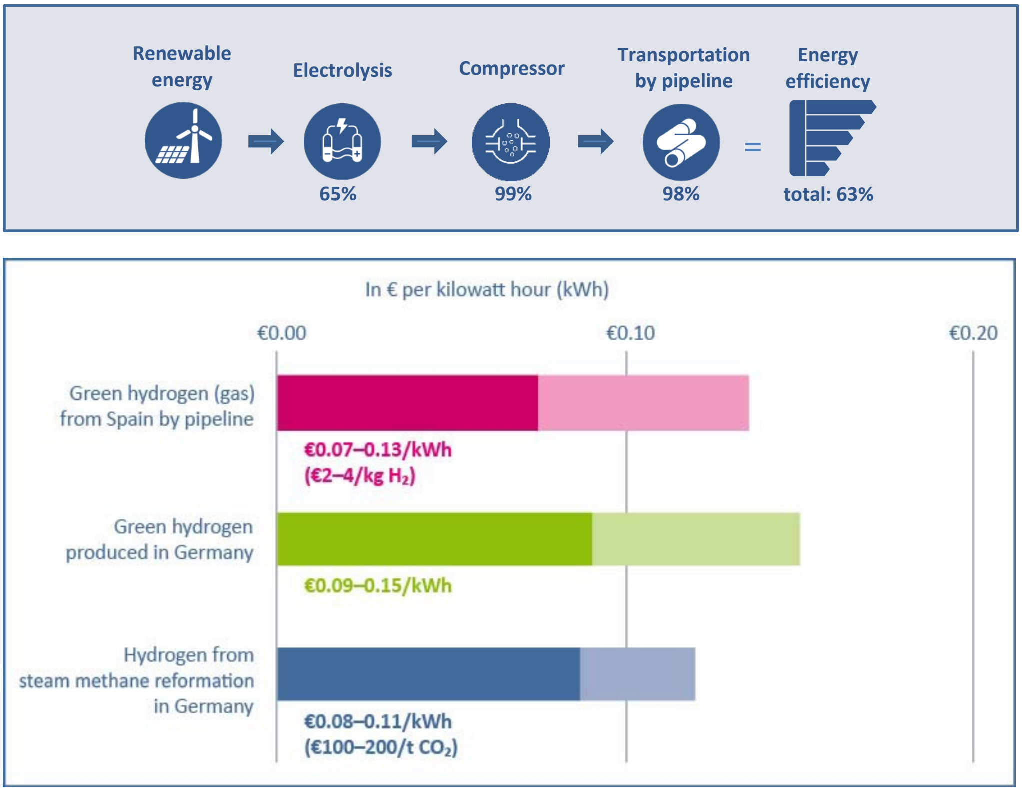


Figure 19: Cost comparison for compressed hydrogen imported into Germany from Spain[89] (source: authors' own calculations).

89 For the technical specifications applied to the calculations presented in the profiles, refer to the corresponding explanations in the reference material (Schmidt et al. 2022).

Special points

- Longstanding, the acceptance of renewable energy usage has been high among the Spanish population and export readiness is generally high too. The country is currently showing that it is strongly committed to producing and exporting green hydrogen. However, both of these points need to be aligned with Spain's efforts to hit its own targets for climate neutrality.
- Spain does also have potential when it comes to producing electricity from renewable sources. But it is expected that much of its capacity will be required to transition away from fossil fuels within its own energy system and supply.
- Spain's geographical proximity to Germany means that transportation by pipeline is certainly feasible. However, its coastline and existing port infrastructures also open up the door to transportation of liquid hydrogen, hydrogen carrier media and synthesis products by ship.
- In order to seize the cost advantages of a pipeline with a large volume, though, significant volumes of green hydrogen would need to be produced in Spain. Exhausting the potential for producing electricity from renewable sources could cause conflict at the local and regional level in the case of large-scale projects and could even lead to direct competition with the potential to jeopardise efforts to make the transition to renewable energy within Spain's own energy system. The production of hydrogen to feed into a larger pipeline[90], for example, would require additional renewable energy amounting to around 35 gigawatts.
- Several regions of Spain grapple with water shortages as it is, but this situation could be set to get worse with the added pressure of water having to be provided for electrolysis – and the outlook for the Mediterranean region in the face of climate change cannot be ignored here either. It is not possible to rule out conflicts when it comes to distribution, with one potential area for concern being the traditionally strong agricultural sector, which is focused on exports. Desalination plants on the coast could be one possible solution provided that they can be operated with cost-effective electricity produced from renewable sources and that the brine by-product can be disposed of in an environmentally friendly way. With those requirements met, the additional costs would be minimal, but the local water supply situation would be vastly improved on the whole.
- As a trade partner within the common EU internal market, Spain has strong trade links with the other EU Member States. The fact that the nation has a democratic constitution and is a member of the EU means that it has a reliable regulatory framework in place for secure investments and strong trade relations. This means that there are also good opportunities for German companies in Spain since they are respected as trade partners. The same applies to the rest of the Iberian Peninsula.

90 The authors worked on the basis of a pipeline with a diameter of 1,016 millimetres and the capacity to transport 56.5 terawatt hours each year, used at 68% of its full capacity to account for the volatile feed-in.

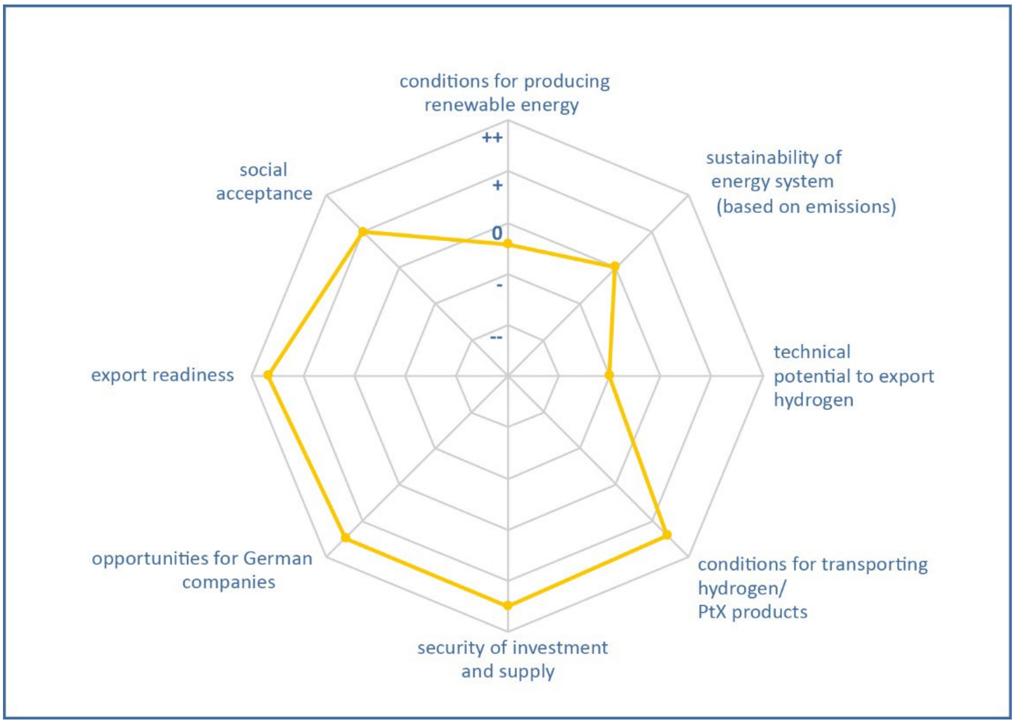


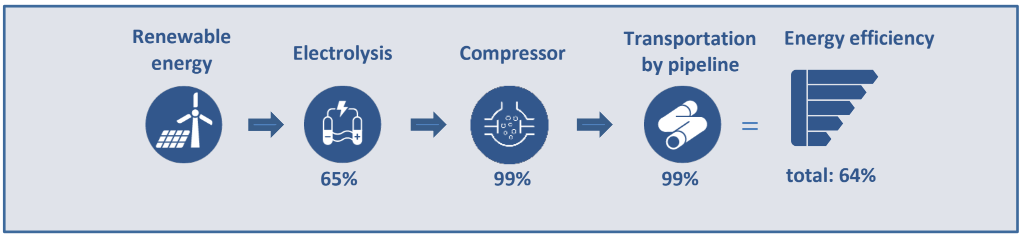
Figure 20: Country analysis for Spain (source: authors' own diagram).

Main challenge

- Any pipeline originating in the Iberian Peninsula would have to pass through other countries, which would have to agree to and support the creation of a new route. Any potential conflicts of interest on an energy, economic, regional and environmental level need to be considered in that respect.

7.2.2 Gaseous hydrogen by pipeline from Ukraine

This profile provides an example of transporting compressed hydrogen in gas form to Germany. Unlike in the Spain example, hydrogen is transported either via a repurposed natural gas pipeline or a new hydrogen pipeline that has been added to an existing natural gas pipeline route. This would reduce the implementation time considerably to around five years and cut down the costs significantly too.



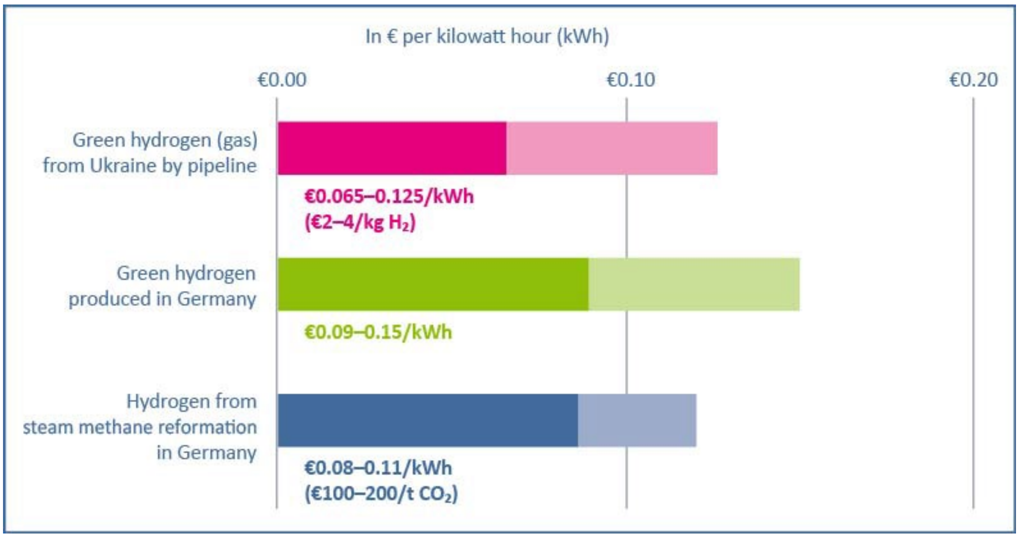


Figure 21: Cost comparison for compressed hydrogen imported into Germany from Ukraine (source: authors' own calculations).

Special points

- The Ukrainian power supply system relies largely on nuclear energy and fossil energy carriers, with a focus on coal. Even before Russia attacked Ukraine, the country was in dire need of modernisation. It can be assumed that supply lines, power plants, energy storage facilities and so much more will require extensive repair and restoration work after the war.
- Until now, regulatory obstacles have stood in the way of renewable energy systems making it onto the market, which has delayed the urgent transformation of the energy system even further. Due to the limited photovoltaic and wind power potential onshore, the country's technical potential for exporting hydrogen can only be assessed as average. Heavy reliance on more expensive offshore wind power could be the only option for leveraging the full potential.
- The only way to seize the cost advantages of a pipeline with a large volume would be to produce significant volumes of hydrogen domestically. This would appear to be extremely challenging, however, due to the impact of

the war, the lack of capacity for producing renewable electricity and the limited experience of installing and operating renewable energy systems. The photovoltaic potential is limited – on a par with the capacity available in the south of Germany. The onshore wind power potential is limited too – by the average wind speeds and the suitable space available. Developing and utilising offshore wind power opportunities in the Black Sea would make it possible to source sufficient renewable energy, but this option would entail additional production costs.

- Developing the renewable energy required to produce hydrogen depends on having access to low-cost capital and companies with experience of installing the relevant systems. Yet Ukraine has been forced to focus on the territorial conflict surrounding Crimea and Donbas for years leading up to the current war with Russia. The political and economic resources required to modernise the energy system that is still based on fossil fuels are simply not available and they have not been for some time now. In the past, corruption was another major problem surrounding large-scale projects[91].

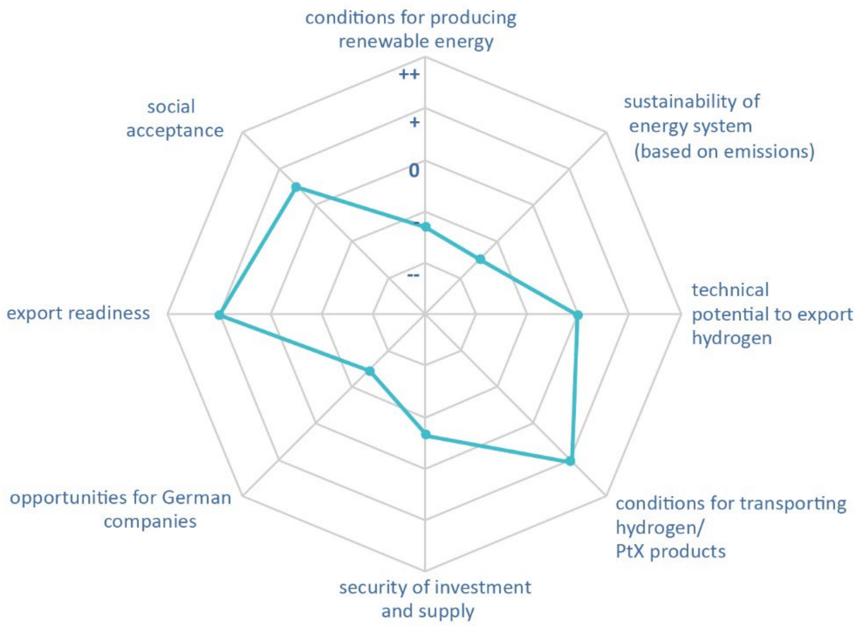


Figure 22: Country analysis for Ukraine (source: authors' own diagram).

- There is a positive attitude towards exports on the whole in Ukraine because they are seen as a source of income. It remains to be seen whether this attitude will be applied to the hydrogen sector – partly because the country needs to reap the benefits of hydrogen and the required renewable energy development for its own energy system first and foremost. This could mean

91 In the Corruption Perceptions Index (CPI), Ukraine ranked in 122nd place out of 180 countries in 2021 (cf. Transparency International Germany 2022).

that Ukraine prioritises domestic use and turns down export opportunities. Overall, it is difficult to judge how accepting the population is towards renewable energy at the moment.

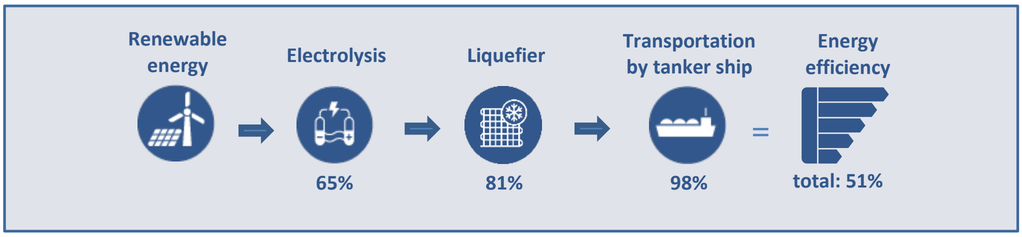
Main challenges

- The biggest challenge facing Ukraine at the moment is the fallout from the ongoing war, especially since it is impossible to predict how long it will go on for and what the extent of the damage will be. Given the country's relevance for Europe in terms of foreign policy, it would be desirable to establish a stronger partnership in the energy sphere for political reasons. The first step was taken back in March 2022, when the connection to the European power grid was extended as an emergency measure. In fact, the power system in Ukraine was fully synchronised with the ENTSO-E Continental European Power System. A hydrogen import/export relationship with the EU on the basis of a new or repurposed hydrogen pipeline could be another step in the right direction after the war.
- Ukraine is in need of a great deal of low-cost capital to modernise its own energy system. The country's efforts to repair and rebuild after the war could provide an opportunity for this because it can be safely assumed that large sums will be made available from around the world. These funds could be invested into the energy system with the specific aim of achieving decarbonisation, reducing the dependency on energy supplies and building the infrastructures required to export energy. Developing the capacity to export hydrogen using existing natural gas pipelines and routes is one way of generating income through exports.

7.2.3 Liquid hydrogen or ammonia by ship from Morocco, representing the Maghreb region

Liquid hydrogen:

This profile provides an example of transporting liquid hydrogen to Germany by tanker ship. In this scenario, cost-effective electricity produced from renewable energy is used to liquefy the hydrogen at the production site. The hydrogen is then transported to its destination port in a cryogenic state on special ships that are still being developed or built as it stands (see Section 8). Depending on what the liquid hydrogen is going on to be used for, it is either loaded into trailers for onward transportation to the end customer or it is converted back to gas and fed into the infrastructure used to distribute hydrogen. The implementation time for transporting large volumes is over ten years – mainly because the fleet of ships required will not be ready any sooner than that.



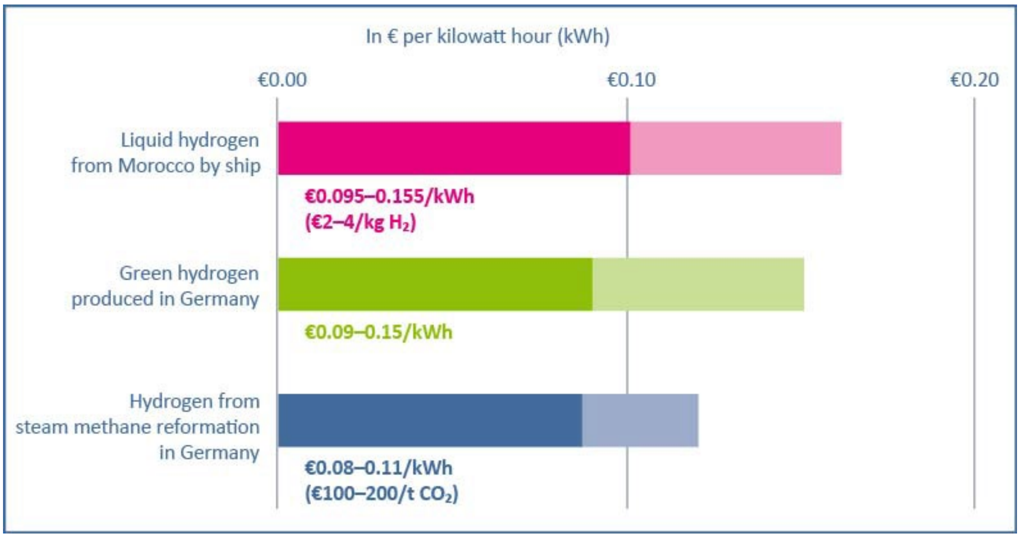


Figure 23: Cost comparison for liquid hydrogen imported into Germany from Morocco (source: authors' own calculations).

Ammonia:

This profile provides an example of transporting ammonia to Germany by tanker ship. In this example, hydrogen is synthesised with nitrogen from an air separation unit on site to produce ammonia (NH_3) in a modified Haber-Bosch process. The ammonia is then pumped into a suitable chemical tanker and transported as a chemical raw material[92]. Existing transportation infrastructures (ports, loading terminals, tanker trucks and trailers) within Europe can be relied upon for the arrival of the ammonia and its onward transportation to Germany. Given the infrastructures already in place, it is estimated that the implementation time would be around two years provided that the ammonia is intended to be used directly within the chemical industry rather than the hydrogen being recovered.

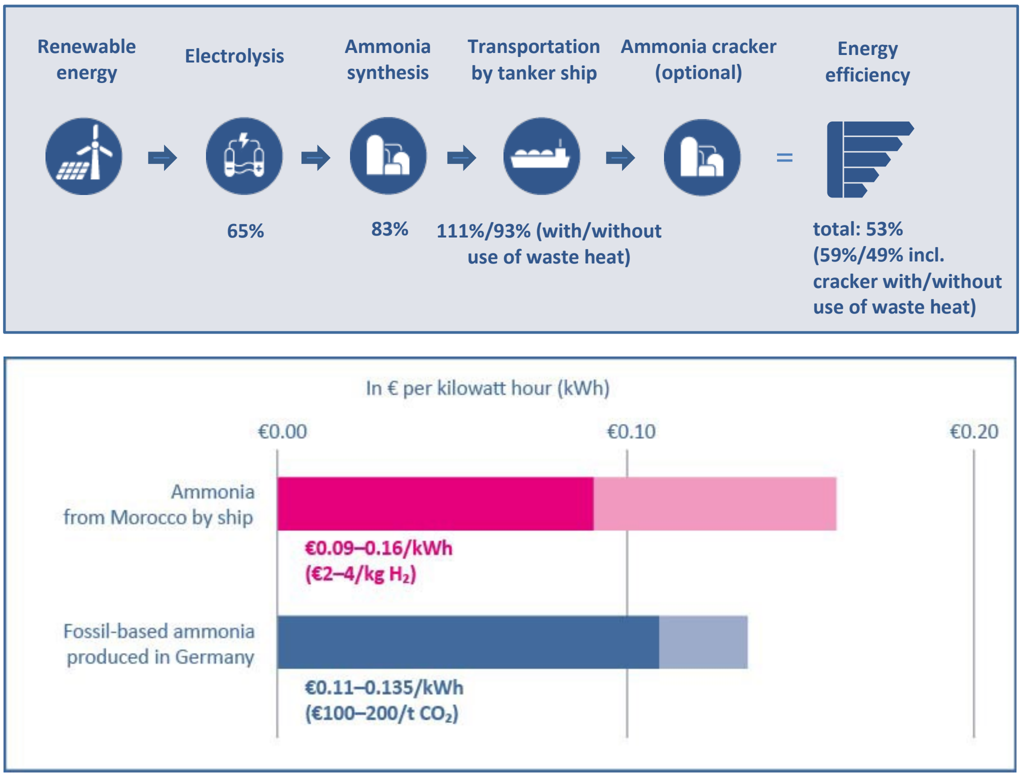


Figure 24: Cost comparison for ammonia imported into Germany from Morocco (source: authors' own calculations).

Special points

- Morocco has additional potential to produce renewable energy. The problem is that using the photovoltaic potential in the south of the country could exacerbate the Western Sahara Conflict. The biggest potential for wind power lies in coastal locations, but these tend to be heavily populated, which means that availability is lacking altogether or very limited. Making the most of the available offshore wind opportunities could improve the situation quite considerably.
- The challenge is ensuring that the creation of an infrastructure for exporting green hydrogen or renewable ammonia does not derail Morocco's own

92 The efficiency exceeds 100% in the figure for the value chain because excess process heat is used for ammonia cracking and not counted as input energy.

targets to transition away from fossil fuel. This could be the case if the capacity to produce electricity from renewable energy was expanded and then used to produce green hydrogen as a priority over replacing electricity produced using coal.

- With conflicts surrounding how land is used already ongoing, commandeering space to produce electricity from renewable energy and to produce green hydrogen could make the situation worse and leave less agricultural space for food production.
- In addition to the land availability the use of water resources is another competitive factor. It would not be a positive development for the production of green hydrogen to make it even harder for the general public to access drinking water or for farmers to access the water they need. Desalination plants on the coast could be one possible solution provided that they can be operated cost-effectively with electricity produced from renewable sources and that the brine by-product can be disposed of in an environmentally friendly way. With those requirements met, this solution is sustainable, involves minimal additional costs by comparison and has the potential to improve the water supply situation locally.
- Morocco's geographical proximity to Europe means that transportation of hydrogen by pipeline is certainly feasible. It would be quicker, though, if existing natural gas pipeline routes could be drawn on. For example, there are plans to decommission one natural gas pipeline running from Algeria to Spain and passing through Morocco[93]. It could be worth investigating the feasibility of repurposing it.
- There are already infrastructures in place that could be repurposed or tapped into to produce ammonia. No ammonia is exported as it stands, however, since it is used directly to produce fertilisers in Morocco.
- Competition is vigorous in Morocco and so German companies may find themselves struggling against other companies from different countries. Against that backdrop, it can be challenging for companies to gain a foothold in the country even though German companies are highly regarded in the country on the whole. There are already a number of energy partnerships to consider. On the other hand, these can be used specifically for local engagement, too.

93 In October 2021, the decision was made to decommission a natural gas pipeline that starts in Algeria and runs through Morocco on its way to Spain. In principle, it could be repurposed as a hydrogen pipeline. This would require Algeria and Morocco to resolve the issues at the heart of the Western Sahara Conflict (cf. El País 2021; European Parliament 2021; Der Standard 2022 and http://www.emplpipeline.com/en (last accessed on: 15/07/2022)).

Main challenge

- From the perspective of German companies, a close political and economic partnership with Morocco and a strong investment situation need to be based on stability and reliability. The conflict surrounding independence for the Western Sahara region, which Morocco occupies currently and has claimed as its own (without international recognition) has led to some difficulties in relations between Germany and Morocco in the past. Although Germany's relationship with Morocco, as with other countries in the Maghreb region, can be considered positive, the conflict could make it difficult to implement joint hydrogen projects with plenty of promise. Companies based in other countries may be in a position to act faster, which could make it more difficult to build new partnerships once any differences have been settled.

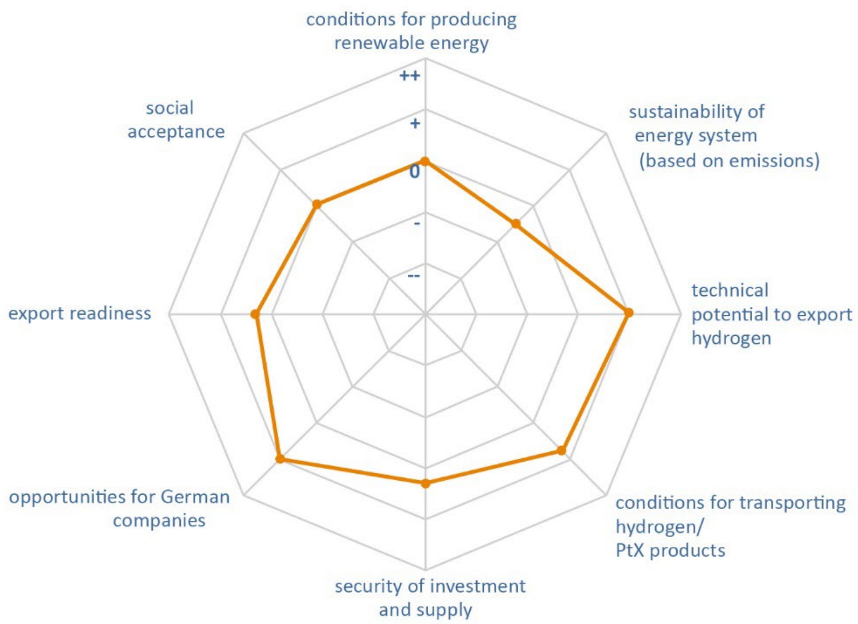
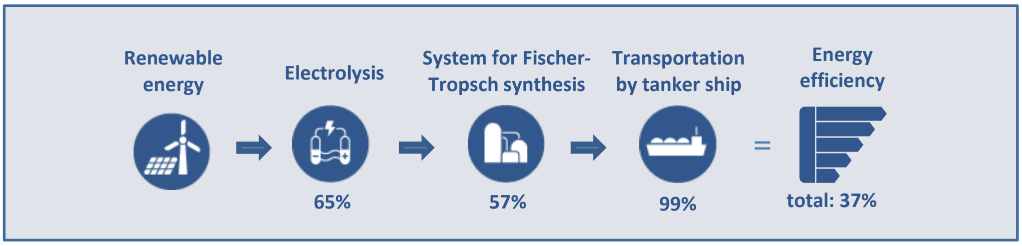


Figure 25: Country analysis for Morocco (source: authors' own diagram).

7.2.4 Fischer-Tropsch product or methanol by ship from Saudi Arabia, representing the Arabian Peninsula

Fischer-Tropsch product:

This profile provides an example of transporting a Fischer-Tropsch product to Germany by tanker ship as a synthetic replacement for crude oil. It involves green hydrogen being produced by electrolysis of water using renewable electricity in Saudi Arabia and converted into a synthetic hydrocarbon mix in a Fischer-Tropsch process using carbon dioxide from industrial processes in the short term and using CO_2 sourced from direct air capture in the medium term. This mix of hydrocarbons would then be exported using the infrastructures already in place for transporting crude oil (including tankers, ports and pipeline systems to refineries). In Germany, this would replace fossil-based crude oil in refineries and allow for the production of climate-neutral alternatives like e-kerosene, e-diesel, e-naphtha and almost all other known by-products within the mineral oil industry. The hydrogen would not be recovered from the Fischer-Tropsch product. If all the existing infrastructures used for fossil-based production and exports were used, the implementation time would stand at around two years provided that concentrated, industrial sources of CO_2 could be relied upon.



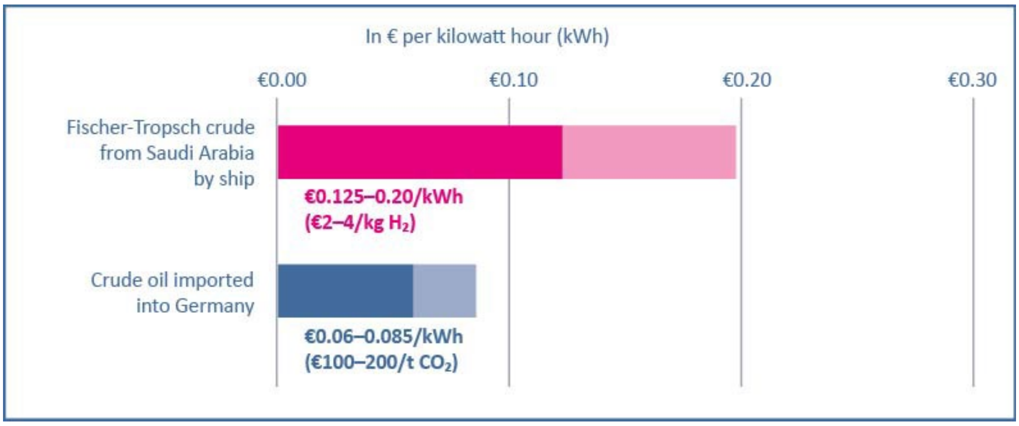
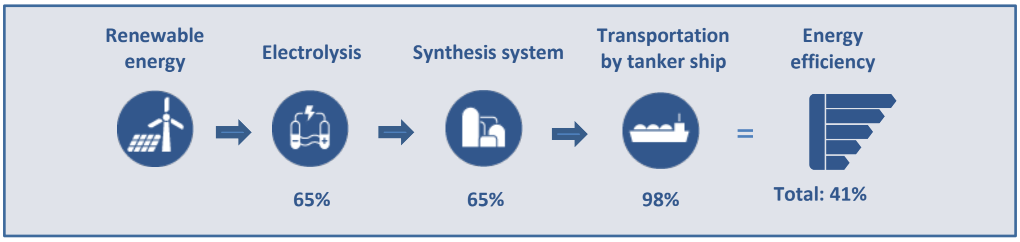


Figure 26: Cost comparison for product of Fischer-Tropsch synthesis imported into Germany from Saudi Arabia (source: authors' own calculations).

Methanol:

This profile provides an example of transporting methanol to Germany by tanker ship as a basic chemical. It involves hydrogen being produced using renewable electricity in Saudi Arabia and then synthesised into methanol using carbon dioxide from industrial processes in the short term and using CO_2 sourced from the air in the medium term. This “green” methanol is exported out of Saudi Arabia using methanol transportation infrastructures that are already in place or will need developing. In Germany, it would replace methanol based on fossil fuels, which can be used as a fuel additive and a chemical raw material within the chemical industry. The hydrogen would not be recovered in Germany. Based on the infrastructures that are already in place and the fact that infrastructures for exporting and importing methanol are set up, the implementation time would be under five years. This estimate is based on the understanding that concentrated CO_2 can be supplied steadily from industrial processes to act as the carbon source required for the process.



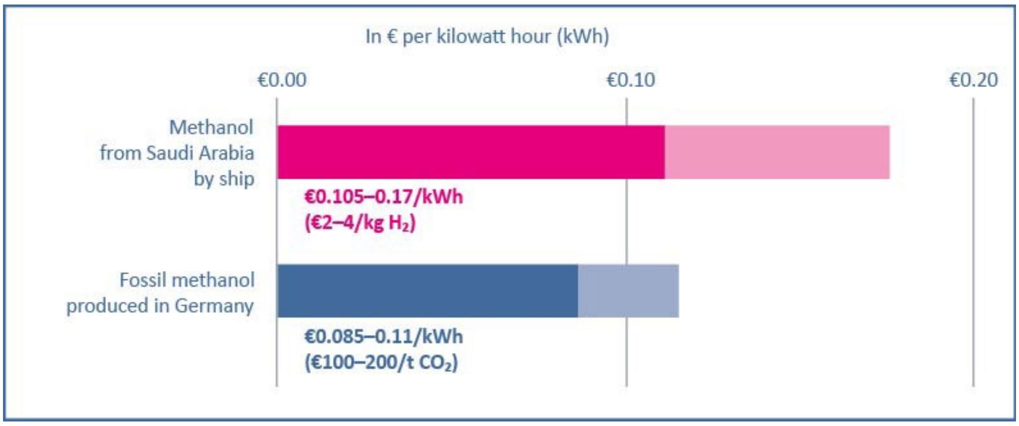


Figure 27: Cost comparison for synthetic methanol imported into Germany from Saudi Arabia (source: authors’ own calculations).

Special points

- In Saudi Arabia, efforts to expand renewable energy are being ramped up. For example, multiple large-scale photovoltaic projects are underway[94] because photovoltaic power can be produced extremely inexpensively in Saudi Arabia. Generally speaking, land required to produce electricity from renewable sources does not tend to be needed for farming or food-growing etc.

94 In 2021, a solar park with an output of 300 megawatts was put into operation, while work is still ongoing on a solar power plant with an output of 1,500 megawatts (cf. IWR 2021).

- As one of the world's biggest exporters of crude oil and the biggest exporter of methanol, Saudi Arabia has existing export infrastructures it could build on to incorporate climate-neutral Fischer-Tropsch products and green methanol.
- Looking ahead to the future, it can be expected that there will gradually be less demand for Saudi Arabia's fossil fuel exports as the focus of the global market shifts to climate-neutral products. This will put the country under increasing pressure to invest in climate-neutral technology so that it is in a position to keep generating sufficient value going forward. This explains why oil exporting companies based in Saudi Arabia (like Saudi-Aramco) and across the wider Arabian Peninsula are ramping up development efforts relating to hydrogen and its synthesis products as well as the renewable energy required for both.
- Although conflict surrounding land usage may not be a problem, it is difficult to predict how accepting the country and its population will be when it comes to the expansion of renewable energy and the option of exporting hydrogen and its synthesis products. The fact that this is difficult to assess outside of the country without much local experience to draw on also comes down to the complicated, very hierarchical social system.

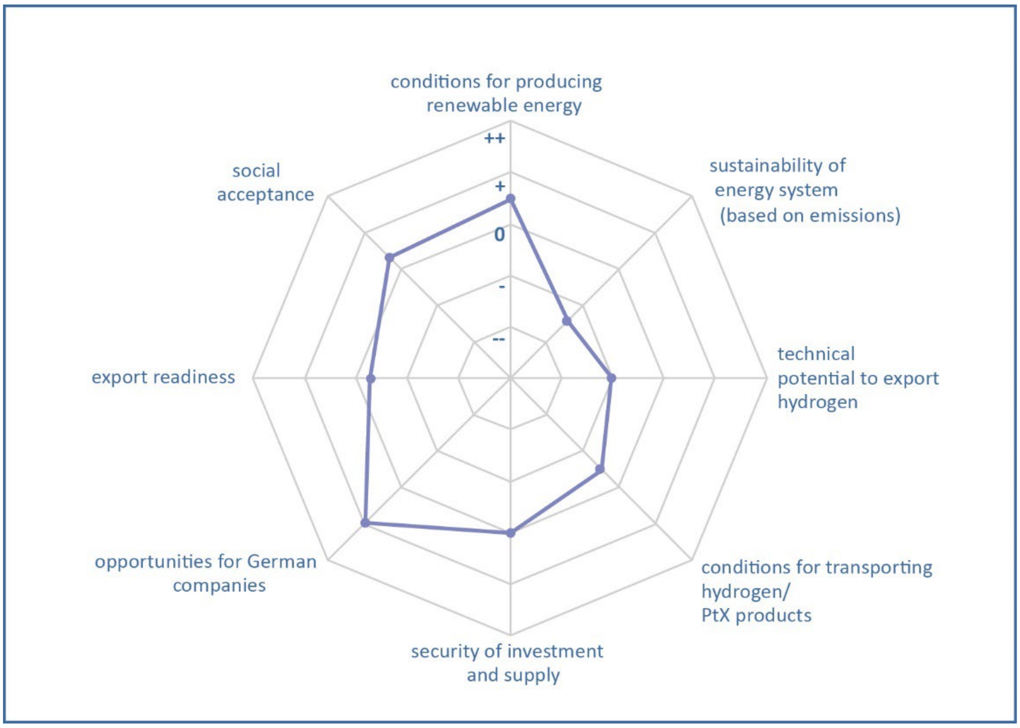


Figure 28: Country analysis for Saudi Arabia (source: authors' own diagram).

- The water required for hydrogen production and synthesis processes could be provided by desalination plants because Saudi Arabia can supply the electricity required from renewable sources very cheaply. Financially speaking, water desalination is a sensible solution because it has very little impact on the overall costs for producing the end products. From an environmental perspective, however, it must be ensured that the brine by-product can be disposed of in an environmentally friendly way to avoid any conflict in that respect.

- Saudi Arabia is representative of the whole Arabian Peninsula in its welcoming attitude towards companies from other countries and Germany in particular. When forming any business relationships here, however, it is important to remember that the legal systems and society as a whole across the Arabian Peninsula have a completely different structure – they are highly religious, autocratic and tailored to the needs of the ruling family/families. The major cultural and legal differences could position these countries as a challenging market for foreign investors. The top-down decision-making processes, in particular for large-scale and high-profile projects that are important to the Saudi leadership's image and reputation (such as Neom), represent strong chances of implementation and good market potential for companies. However, generally these projects do not include opportunities for people affected by building plans, civil society groups or local workers.

Main challenge

- The shocking human rights situation in Saudi Arabia[95] could prove problematic for German companies looking to do business here – in terms of the local conditions surrounding the project, the public perception and efforts to uphold mandatory external or internal standards. When implementing specific projects, it would be necessary to consider the fact that working conditions on large building sites are often criticised and look into the way that people who are affected by the project work are treated (such as with regard to relocation, land expropriation and conflicts surrounding the use of natural resources).

95 On top of Saudi Arabia's involvement in the war in Yemen, which is responsible for a high victim count and precarious living conditions in the country, criticism often focuses on the use of the death penalty, the persecution and torture of people deemed to be in opposition and long sentences for people who publicly criticise the authorities in Saudi Arabia. The working and living conditions of migrant workers are often problematic too (cf. Amnesty International 2022, page 316 ff.; cf. Human Rights Watch 2022, page 569; cf. OHCHR 2022; cf. German Bundestag 2020).

7.2.5 Liquid organic hydrogen carrier (LOHC) or Fischer-Tropsch product by ship from South Africa, representing Sub-Saharan Africa

LOHC:

This profile provides an example of having hydrogen absorbed by an LOHC and transported to Germany by tanker ship. It involves hydrogen produced on site using electricity from renewable sources being absorbed by a carrier molecule like benzyltoluene in a synthesis process to create a liquid organic hydrogen carrier or LOHC. This LOHC is similar to diesel in its properties and behaviour. In other words, it can be assumed that existing infrastructures in place for diesel and mineral oil could potentially be repurposed or tapped into for this LOHC option. This means that the LOHC can be loaded onto tanker ships in South Africa, transported to Germany and dehydrogenated centrally upon arrival at the port. This process requires an external heat source. The hydrogen released may need to be purified before being supplied if it is going to be used in an application with strict purity requirements. The carrier medium must be returned to South Africa by ship ready to be loaded up again for the next cycle. It is expected that it would take around ten years to implement this option on an industrial scale.

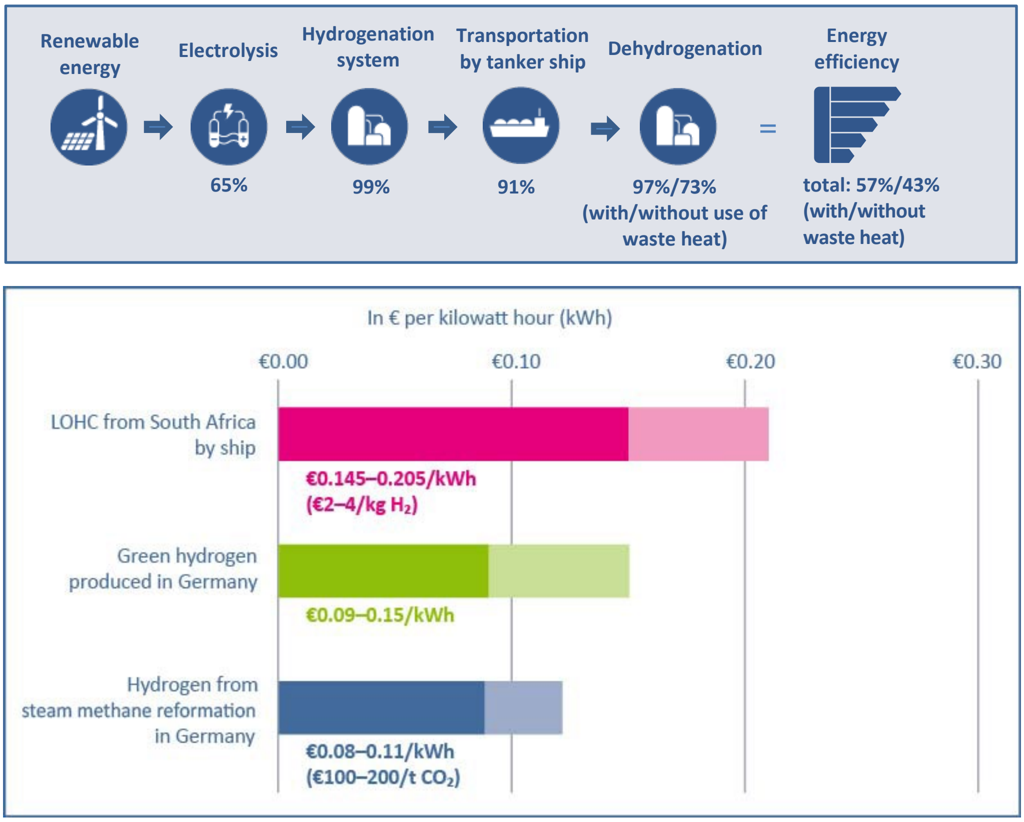
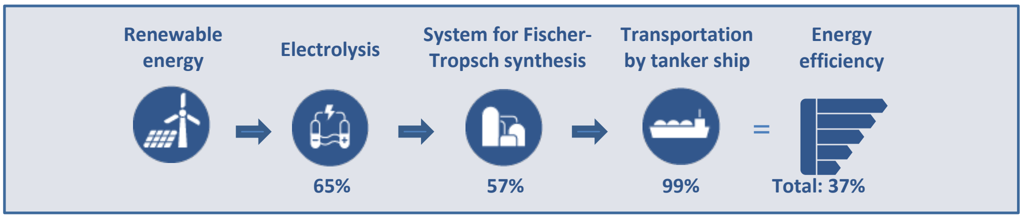


Figure 29: Cost comparison for hydrogen absorbed by LOHC and imported into Germany from South Africa (source: authors' own calculations).

Fischer-Tropsch product:

This profile provides an example of transporting a Fischer-Tropsch product to Germany by tanker ship as a synthetic replacement for crude oil. It involves hydrogen being produced by electrolysis of water using renewable electricity in South Africa and converted into a synthetic hydrocarbon mix in a Fischer-Tropsch process using carbon dioxide from industrial processes in the short term and direct air capture in the medium term. As a replacement for or addition to the fossil fuel crude oil, this mix of hydrocarbons would then be exported using the infrastructures already in place for transporting crude oil (including tankers, ports and pipeline systems to refineries). In Germany, this would replace fossil-based crude oil in refineries and the petrochemical industry and allow for the production of climate-neutral alternatives like e-kerosene, e-diesel, e-naphtha and almost all other known by-products within the mineral oil industry. The hydrogen would not be recovered from the Fischer-Tropsch product. Given the infrastructures already in place for crude oil in Germany and South Africa, it is estimated that the implementation time would be around two years if the carbon could be sourced from industrial point sources.



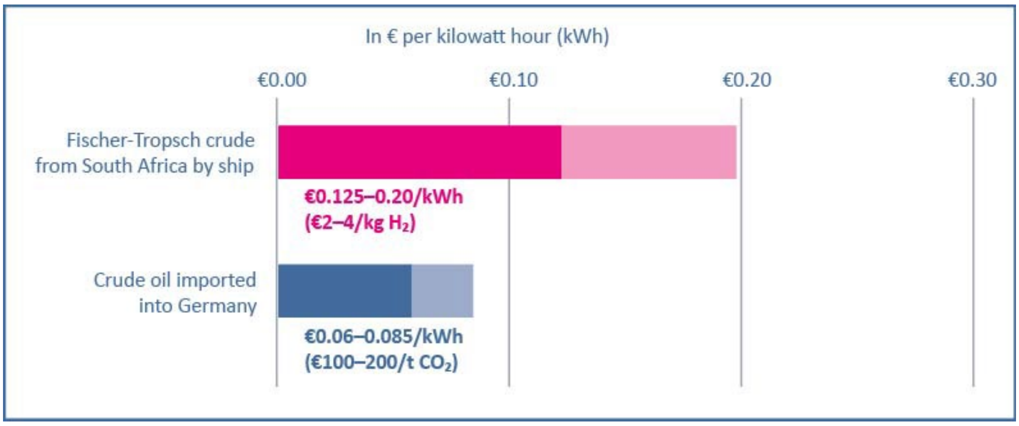


Figure 30: Cost comparison for product of Fischer-Tropsch synthesis imported into Germany from South Africa (source: authors' own calculations).

Special points

- South Africa has good potential for producing renewable electricity from photovoltaic and wind power onshore and very favourable conditions for offshore wind power.
- The energy system in South Africa relies heavily on fossil energy carriers as it stands, with a particular focus on coal. When developing renewable energy and establishing partnerships for green hydrogen production, it is

important to ensure that any potential plans to export hydrogen or its synthesis products do not jeopardise efforts to move the energy system in South Africa away from fossil fuels.

- South Africa has much expertise in Fischer-Tropsch synthesis. Despite the fact that it has only been used for the purpose of converting coal into liquid hydrocarbons so far, intensive development work can be expected in the field of synthetic hydrocarbons in the future.
- In South Africa, the land required to produce renewable energy is often also needed for growing food, so there could be scope for exacerbating existing conflicts surrounding the use of land.
- Beyond the issues relating to land availability, conflict surrounding the use of water resources could be further cause for concern. For this reason, it is important that the use of electrolysis to produce hydrogen does not worsen the existing challenge of supplying the population with drinking water and giving farmers access to the water they need. The desalination of seawater at production locations along the coast could provide another source of water. This would be a financially viable option because the production of electricity from renewable sources is cost-effective, but environmental aspects like the disposal of the brine by-product also need to be considered.

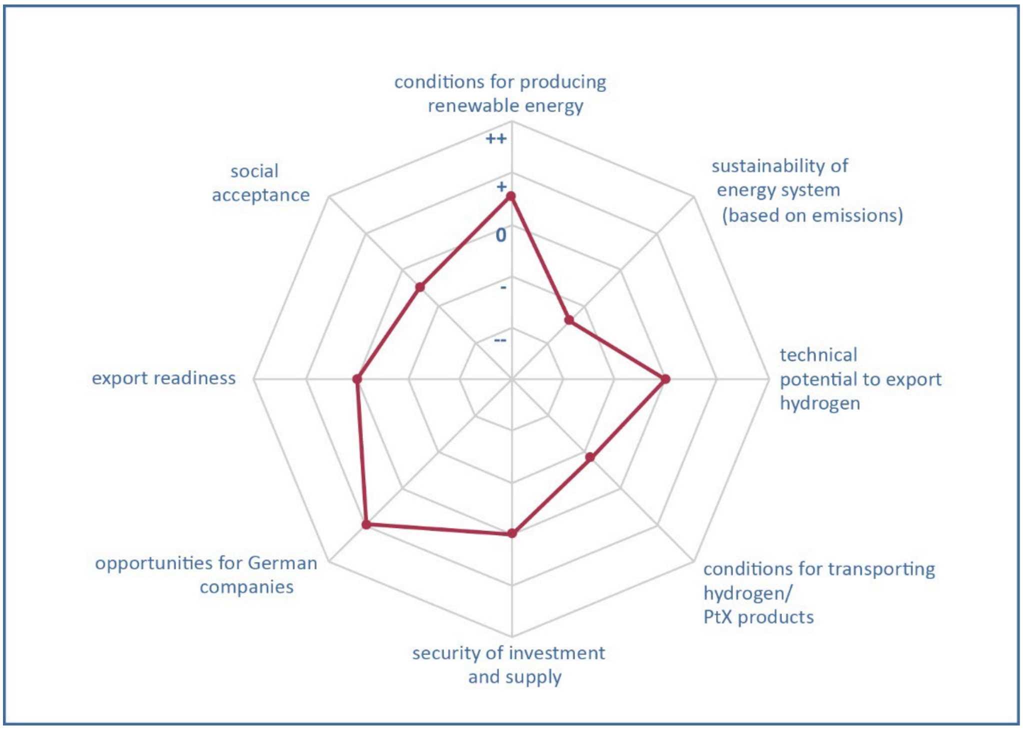


Figure 31: Country analysis for South Africa (source: authors' own diagram).

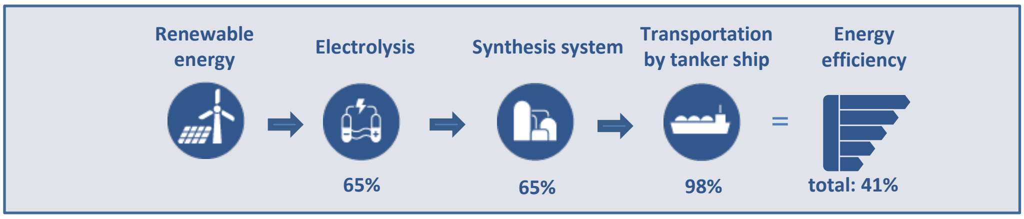
- At present, work to develop the renewable energy supply is being driven almost exclusively by major investors. The general public do not tend to benefit from these kinds of projects – a situation which has the potential to exacerbate the ongoing societal conflicts, including those relating to the distribution of wealth. Any such negative experience associated with the development of renewables could cause the population to oppose the production of hydrogen and view it in an equally negative light.

- German companies have a good reputation in this region, providing a solid foundation for future projects. Legal issues are a cause for concern, however, because some local practices are far removed from the European standard and corruption[96] can be a problem.
- It is also worth bearing in mind that China has a strong presence in Sub-Saharan Africa, meaning that potential partners in South Africa could already be tied by other contractual obligations.

96 In Transparency International's Corruption Index, South Africa ranked in 70th place out of 180 countries in 2021 (cf. Transparency International Germany 2022).

7.2.6 Methanol by ship from Brazil, representing South America

This profile provides an example of transporting methanol to Germany by tanker ship as a basic chemical. This option involves hydrogen being produced by electrolysis of water using renewable electricity in Brazil. That hydrogen is then used with carbon dioxide from industrial processes (in the short term) or from direct air capture (in the medium term) to synthesise methanol. The "green" methanol produced in this way is then transported by ship using the infrastructures already in place for methanol. In Germany, it would replace methanol based on fossil fuels, which is used as a fuel additive and a chemical raw material in the chemical industry among other things. The hydrogen would therefore not be recovered in Germany. Given the infrastructures already in place, it is estimated that the implementation time would be around two years if industrial CO_2 point sources could be used.



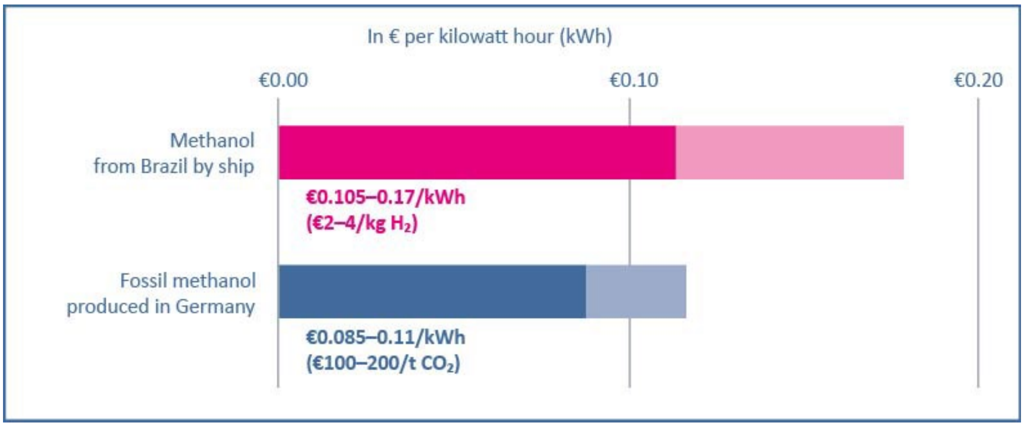


Figure 32: Cost comparison for synthetic methanol imported into Germany from Brazil (source: authors' own calculations).

Special points

- Brazil has good potential for producing electricity from renewable sources. The local solar radiation conditions and offshore wind power potential are particularly favourable. The conditions are also good for onshore wind power. Hydropower is already being used on a large scale too.
- By using the existing hydropower plants and biomass (increasingly ethanol made from sugar cane), Brazil was able to cover around 47% of the total energy consumed by end users[97] with renewable sources by 2018. As a result, it can be assumed that it will not be long before the country will have even larger volumes of renewable energy available for potential export

97 Cf. IRENA 2018.

opportunities. On that basis, Brazil’s technical potential to export hydrogen can be rated as good.

- Interest in hydrogen has grown significantly in Brazil, as demonstrated by the creation of a hydrogen roadmap, for instance. At the time when this analysis paper was being written, that roadmap was not available and so it could not be covered in the results.

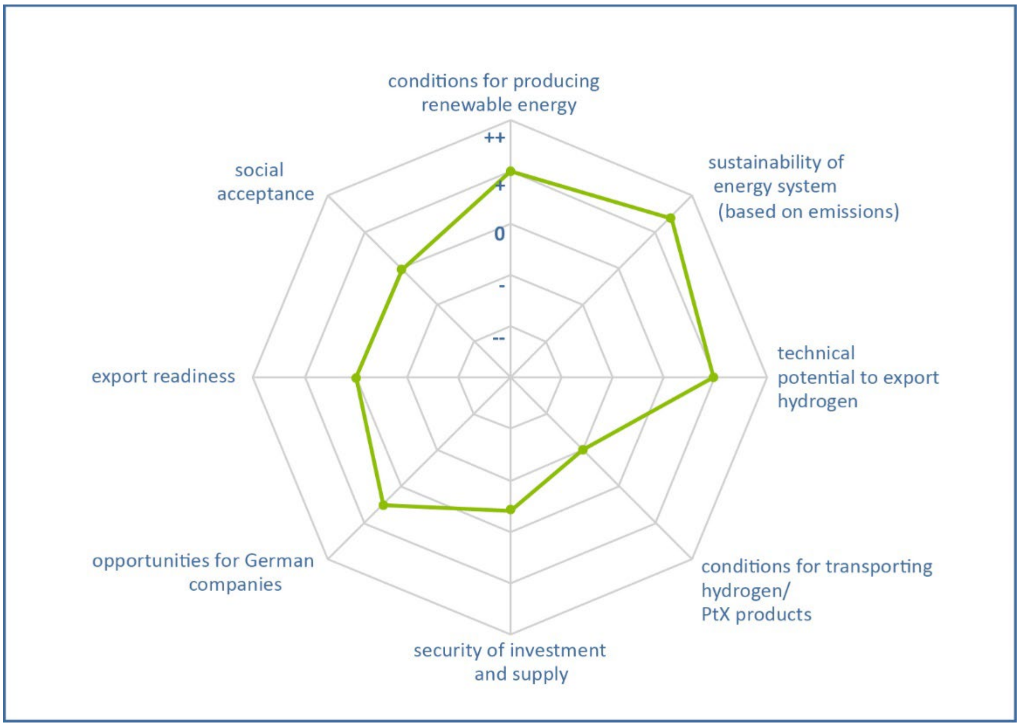


Figure 33: Country analysis for Brazil (source: authors’ own diagram).

- In some regions, the population has serious reservations about expanding the production of electricity from renewable sources because in the past some large-scale hydropower projects in particular have been unlawful and have been implemented without any regard for the environmental impact, the cultural heritage of indigenous communities or the living conditions of people affected by them. This experience has created a critical attitude towards the production of electricity from renewable sources and could cause proposals to produce green hydrogen to be rejected. On that basis, it is essential that laws are enforced, cultural heritage is respected and relevant groups in society are directly involved in projects aimed at sustainably expanding renewable energy with a view to ensuring acceptance among stakeholders and strengthening support within the wider population.
- The good potential for exporting renewable energy is limited by the conditions for transporting hydrogen and PtX products as it stands. They are far from favourable at the moment due to Brazil’s average result in the logistic performance index along with the long distance to be covered

between Brazil and Germany. Corruption could be another cause for concern when working on projects.[98]

- As a sustainable basic or platform chemical, methanol could open up new opportunities for value creation for Brazil and other countries in South America. Further investigation is required, however, to check whether any other potential transport options might provide a more favourable foundation for creating an export infrastructure for hydrogen synthesis products or other products alongside synthetic methanol. For example, Brazil already imports ammonia. If the existing import infrastructures could be converted to export infrastructures, it could also be possible to export renewable ammonia and create that added value domestically.
- Germany has a long tradition of collaborating with Brazil, which also applies to other South American countries like Argentina and Chile. German companies have a strong presence in these countries and there is a great deal of interest in building import/export relationships with Germany even though other countries have a presence there too. Uncertainty in this regard may stem from the fact that, as mentioned previously, existing laws and regulations are not respected properly – especially in relation to the environment.

98 In Transparency International's Corruption Index, Brazil ranked in 96th place out of 180 countries in 2021 (cf. Transparency International Germany 2022).

8 Obstacles and implementation requirements

The working group has focused on presenting the options for transporting (green) hydrogen and exploring the best ways of implementing them in Germany before the year 2030. An essential part of this is overcoming any obstacles standing in the way of importing hydrogen, building global markets and establishing hydrogen partnerships. Successful implementation also requires plenty of opportunities to test, learn and find solutions collaboratively. This section addresses and discusses the challenges facing the ramp-up of hydrogen imports as identified by the working group and introduces potential solutions.

8.1 Direct implementation challenges and development requirements of a technical nature

Whether or not the transportation options can be implemented depends largely on **progress with technological developments**. Almost all of the options investigated by the working group involve ongoing research, development and scaling efforts. As long as a targeted research agenda and dedicated funding is provided, it can be assumed that any technical elements that are not ready now will have been sufficiently developed and scaled up for commercial use by the year 2030. The scope of the development work required for each transport option to be feasible does vary quite considerably in some cases, however.

Transportation of compressed hydrogen by pipeline

The option of transporting gaseous hydrogen by pipeline is already available, with the technology having been developed on an industrial scale. In other words, there are no technical reasons why this option cannot be implemented by 2030. There could still be room for development as far as the operation is concerned, though. To be specific, this relates primarily to the possibility of pressure swing operation with storage as an additional function, which could bring benefits relating to finances and the energy system but also potentially cause challenges relating to material stress.

Transportation of liquid hydrogen by ship

For liquid hydrogen, all the elements in the process chain are available in principle but they are not yet ready to be applied on a broader commercial scale. There are some major technical challenges that are likely going to take a long time to overcome. On that basis, there is much uncertainty surrounding the feasibility of importing the volumes of liquid hydrogen required to make a difference to the energy sector by 2030. In fact, it is unlikely to be a viable option.

Liquefication technology is one area of development required to be able to achieve large production volumes and high levels of energy efficiency. Before liquid hydrogen can be transported by ship on the necessary scale, large ships designed to transport hydrogen over long distances with minimal boil-off need to be built as well. Currently, it is only Asian shipyards that are working on this development by testing out smaller ships (see Section 6). Considering the ports, infrastructures for the arrival and distribution of liquid hydrogen need to be established first.

Transportation of LOHC by ship

Three elements need to be built up in an industrial scale for the liquid organic hydrogen carrier option: carrier material production, hydrogenation systems and dehydrogenation systems.

At present, carriers referred to collectively as LOHC are only produced in relatively small volumes on the basis of crude oil[99]. If LOHC are to be used more broadly, the relevant capacity for (climate-neutral) production and preparation needs to be secured. In addition, the systems used to hydrogenate the carrier medium need to be scaled up. It would be advantageous to develop integrated concepts so that the heat released during the process could be utilised at the production site.

For the use of LOHC as a hydrogen carrier medium to be economically attractive, decentralised applications need to be developed as a priority, including options for dehydrogenation and recovery of the carrier medium at the point at which the hydrogen is going to be used. An appropriate system for returning the carrier medium cannot be forgotten here. After all, it seems unlikely that the heat sources required for dehydrogenation at the relevant high temperatures (300 degrees Celsius) will be accessible free of charge centrally in the future when the energy system releases zero greenhouse gas emissions. However, if this heat is not free of charge, dehydrogenation of LOHC is not a financially viable solution. Meanwhile, the creation of the decentralised LOHC infrastructure mentioned above is currently expected to be time-consuming, costly and complex – even with the option of building onto existing infrastructures.

99 It is estimated that 7,500 tonnes of dibenzyltoluene, which is combined with benzyltoluene during production, are produced around the world every year as it stands, which equates to around 10% of the full load of a large chemical tanker (cf. HySTOC 2019).

Transportation of ammonia by ship

Fossil-based ammonia is already transported as a chemical raw material and put to all kinds of uses. Renewable ammonia can be used as a direct replacement for fossil-based ammonia without the need for any further development. Port facilities and ships are already available to some extent and the technology has been sufficiently developed, so there is no technical obstacle stopping this option from being implemented in plenty of time for 2030. Before ammonia can be used as energy or as a hydrogen carrier, one of the process steps would need to be developed or scaled in each case – the techniques for using ammonia as energy carrier respectively the crackers required for dehydrogenation. Development for both of these elements is underway, with a focus on ammonia being used as fuel within the maritime sector[100]. The development, scaling and implementation of efficient dehydrogenation technologies on an industrial scale will take time. Ammonia is also highly reactive and toxic, which means that safety aspects need to be considered carefully when transporting and storing large volumes. This might incur considerable additional costs.

Transportation of methanol by ship

When it comes to transporting methanol by ship, two key aspects of the process are not yet workable on a commercial scale: the climate-neutral supply of large-volumes of carbon dioxide and the systems required for synthesis. In each case, the technical processes are familiar and similar to other chemical processes that have been established on a large scale, but they have not yet been implemented industrially themselves.[101] As far as the supply of carbon dioxide is concerned, the challenge lies in scaling up the concentration process (for example for CO_2 sourced from cement production or the air). The potential to make considerable savings on costs also needs to be exploited so that the target costs assumed for the calculations in Section 4 on the basis of values taken from the literature can be met or ideally cut even further. Methanol synthesis needs to be adapted to accommodate a different educt – carbon dioxide instead of carbon monoxide, which was extracted from source materials rich in carbon using a water-gas shift reaction.

Transportation of Fischer-Tropsch products by ship

The situation for the widespread introduction of a synthetic substitute for crude oil is similar to the situation for methanol. The climate-neutral supply of large volumes of carbon dioxide and synthesis on that basis are technically possible

100 MAN and Wartsilä are two companies working on ammonia engines (for further information in German, see https://www.man-es.com/docs/default-source/press-releases-new/20201021_man_es_pr-aengine-mes_de.pdf (last accessed: 15/07/2022) and https://www.wartsila.com/docs/default-source/local-files/germany/energy-business-documents/220506_wartsilaa_paper_futurefuels.pdf?sfvrsn=c2a39c44_6 (last accessed: 15/07/2022)). The "ShipFC" EU research project is working on the scale and trialling the use of a high-temperature fuel cell combined with an ammonia cracker to propel a ship (see the project website: https://maritimecleantech.no/project/shipfc-green-ammonia-energy-system/ (last accessed: 15/07/2022)).

101 But, as one example, Swiss company "Climeworks" is already producing systems that can be used to capture CO_2 from the air – albeit on a small scale (cf. Climeworks 2022).

but not yet available on a large enough scale. As a priority, efficient direct air capture technology to extract CO_2 from the air needs to be developed, scaled and implemented on an industrial scale as soon as possible. Relying solely on the use of CO_2 point sources will not deliver the volumes required[102] to advance the technology for producing a climate-neutral synthetic replacement for crude oil to its full potential. Without this development, there will anywhere near as much potential be exploited to protect the climate e.g. within the chemical industry or refineries.

Transportation of methane by pipeline

The development required for this option also corresponds to the situation for methanol and Fischer-Tropsch products, as outlined in the two previous sections. The Sabatier reaction is used on a large scale at this stage, but only to eliminate carbon monoxide and not to produce methane.

8.2 Implementation requirements relating to cross-border collaboration

Alongside the technological developments, successfully importing hydrogen depends on outstanding questions being addressed with countries of origin but also any **countries that would need to be passed through**. This applies above all to the options involving pipelines because – unless partnerships are between countries that are direct neighbours – those pipelines have to pass through other countries that also have to agree to the construction work. For example, a pipeline running from the Iberian Peninsula to Germany would have to pass through France. Conflicts of interest on an energy, regional and environmental level need to be considered with regard to the two countries at either end and any other countries in between since they may have a significant impact on implementation times.

The development of a green hydrogen economy and **changes to supply infrastructures within the energy sector** could also have a huge impact on the conditions and security of supply in partnering countries. Potential conflicts of interest need to be anticipated at an early stage and proactively addressed to avoid causing any new conflicts or exacerbating existing conflicts. As a general rule, this requires a thorough approach involving a wide spectrum of stakeholders from politics, industry and society.

With regard to **hydrocarbons**: If industrial point sources are to be used to **source carbon dioxide** for Fischer-Tropsch products initially due to costs and a lack of direct air capture technology available on an industrial scale, special attention needs to be paid to the **sustainability of processes**. Most importantly, there must be no chance of the use of fossil energy carriers being increased or prolonged unnecessarily in the exporting countries. Partnering

102 Refer also to the deep dive at the end of Section 4.

countries looking to export must not end up jeopardising their own efforts to achieve climate neutrality. This could happen, for example, if they exhaust all the most cost-effective locations for renewable energy for hydrogen exports and do not leave enough scope to be able to transition their own domestic energy supply away from fossil fuels as a result.

If the green hydrogen economy is to be ramped up successfully, a series of further requirements must be met, having been addressed within the scope of further investigations. To be specific, value added locally, support within the population, environmental impact and **infrastructures in the producing countries** are all aspects to be looked into in depth. It is often the case that the regions with the best potential for producing renewable power do not have the network infrastructures required to produce large volumes of electricity and hydrogen in the gigawatts (or at least they do not yet). Another aspect to be clarified is whether infrastructures can be accessed without discrimination.

As the analysis of the options presented by way of example (Section 7) demonstrates, each of the potential partner countries has definite strengths and weaknesses that would need to be balanced out as effectively as possible in dialogue with them. The working group is keen to point out that new energy partnerships will only be successful if they are **established on an equal footing**. That means that joint projects have to lead to financially, socially and environmentally sustainable development within each of the countries in a partnership.

8.3 Implementation challenges relating to the regulatory framework

As revealed by two legal reports commissioned by the working group, **there is not yet a coherent regulatory framework on an international, European or national level**, which means there is no uniform law underlying the hydrogen economy.[103] The regulatory framework for the production, transportation and usage of hydrogen is currently fragmented at best. Green hydrogen is not even covered in many regulatory areas. Without a strong and coherent regulatory foundation, the green hydrogen economy is not being sufficiently governed as it develops. There are no legally sound incentives in place to support the ramp-up of new technologies.

Reliable legal regulations all the way along the value chain for green hydrogen and its synthesis products, which have been agreed across political levels (global agreements, EU, Federal Republic of Germany, federal states within Germany), are essential both for establishing trade relations internationally and within Europe and for enabling companies to make investments in this field and demonstrate ongoing commitment to it. It is crucial that the

103 Cf. IKEM 2021; cf. Stiftung Umweltenergierecht (Environmental Energy Law Foundation) 2021.

principle of equal treatment is applied as a minimum standard so as not to jeopardise domestic production of hydrogen. This means that imported hydrogen must meet the same requirements as hydrogen produced domestically or within the EU.

The fact that regulatory requirements have not yet been stipulated fully or at all is causing uncertainty among technology developers, producers and suppliers as well as investors, funding providers, project developers and companies that are looking to switch to hydrogen technologies on the consumer side or keen to get involved in the business of importing hydrogen. This kind of uncertainty among key stakeholders is stalling the development of the market for green hydrogen on every level and delaying the swift ramp-up being targeted.

8.3.1 Transparent regulations on certification and accountability for a swift ramp-up

When it comes to importing hydrogen, the **certification** of hydrogen and its products being transported and their **accountability** against **climate protection commitments** in the receiving countries – in this case the EU and Germany – are of critical importance.

For imports coming from countries outside of the EU in particular – if not exclusively – there is a conflict between meeting sustainability requirements and conditions encouraging investment to ensure a swift ramp-up. With a view to allowing stakeholders within the hydrogen economy to make plans with some level of confidence and invest accordingly, this (assumed) conflict needs to be resolved as soon as possible if significant volumes are to be imported by the year 2030.

From a state perspective, setting up a certification system early on that defines the mandatory criteria also serves the purpose of establishing **global minimum standards**. This will stop bilateral agreements and contracts becoming widespread quickly despite being based on such a broad range of criteria that it would be a nearly impossible task to consolidate them later down the line.

If international hydrogen trade is to be established on an equal footing, **a certification system** needs to be developed and **implemented** as a priority to provide a consistently reliable source of information relating to hydrogen as a product. The starting point is to define the limits of the certification system. In other words, the point at which the value chain begins must be made clear. This will ensure there is no doubt as to the point at which information about greenhouse gas emissions and more is first collected and disclosed in relation to the value chain. Once the limits of the system have been defined, two essential steps must be taken:

- **First of all**, the **chain of custody** (product/control chain) for climate-neutral hydrogen must be determined. This stipulates which information can be made available at each stage of the value chain and which data needs to be collected to track the balance along the entire value chain – from the production of electricity from renewable sources and the production of hydrogen to storage/processing, transportation and use.

  There is a need for formal clarification of the criteria and steps along the value chain, the collection systems to be created, the process for passing on information between each of the individual stages of the value chain and the process for balancing.

  The requirements applicable to the information to be disclosed in a chain of custody can cover a range of aspects. For example, in a mass balance system, the certified volumes have to be specified in proportions rather than being physically identifiable. It might also be necessary to disclose data on upstream greenhouse gas emissions if the carbon footprint needs to be documented for the hydrogen. Other environmental and social aspects can also be certified along the chain of custody. In this case, it is generally sufficient to provide proof that every company in the chain meets the sustainability requirements as set out by the certification system. In other words, every company has to be certified.

- **Secondly**, it is down to state representatives to decide upon the **criteria** for certification that are to be applied within the specific subsidy scheme to ensure that it is clear which criteria need to be met at each stage of the chain of custody and along the entire value chain.

  At the moment, this is only provided within the scope of the Renewable Energy Directive (RED II) for approval of hydrogen and electricity-based renewable fuels of non-biological origin (RFNBO) within the transport sector – and even then the regulations are not yet conclusive. But these criteria are not in place in other areas where hydrogen is used, which could cause uncertainty among potential market players and delay the market ramp-up.

  While information along the chain of custody is required at all times and in every system, the **criteria** that apply to certification **can change over time**. For example, certain requirements and criteria may not apply to pilot projects (to start with) to allow for an information system to be built up. It is also an option that industry-specific default values are applied during the pilot phase instead of specific operational values for individual criteria being required. Another ideal strategy would be to introduce grandfathering for initial pilot projects that still have gaps in certification owing to missing regulations. In this scenario, the hydrogen produced could be certified as green for the amortisation period of the first electrolysers and counted towards the relevant sector targets.

With transparent certification in place, it would be possible to demonstrate the feasibility of importing green hydrogen, encouraging it as an option and addressing any issues relating to acceptance among the population in the process. However, it is also worth mentioning that certification systems tend to place high demands on technology during the market entry phase, which can scare off potential new market players if there is no mechanism for financial compensation or no attractive financial incentive in place. The aim should be to determine the information required early on and gradually develop a suitable data collection system as the market emerges. With full transparency in mind, the future target system should be set out with reasonable granularity and the pathway to achieving targets should be described in enough detail that uncertainty and related risks can be minimised for all market players from the outset.

The **information and data collection systems** should be developed (further) in line with the market ramp-up as should the associated **documentation** for tracking compliance with the certification steps. The idea is that all the information should be available and the certification system should be ready to use to its full extent by the agreed point in time. This could be after pilot projects have been implemented or after a defined pilot phase has been completed. It should be noted that the way in which the regulatory framework is set up, for example in line with the funding tools and the corresponding criteria that need to be met to be awarded funding, determines (at least in part) which elements from the developed information chain are needed on a case-by-case basis.

8.3.2 Uniform regulatory framework or stronger steering effect through differentiation

From the point of view of the government, which is responsible for laying down the regulations at the heart of the newly emerging hydrogen market, certification creates a transparent foundation of information that can inform the process of developing funding tools. Setting criteria and specific properties for hydrogen that falls under the relevant subsidy scheme (which can be demonstrated using the information collected along the chain of custody) provides the government with a way of encouraging or prioritising the use of hydrogen in specific sectors, provided that the requirements vary across different sectors and other types of revenue streams are not available to compensate for any of those differences.

The delegated act on the current version of the Renewable Energy Directive (RED II) is an example, setting out the requirements for hydrogen that is to be counted towards the EU targets for reducing greenhouse gas emissions within the transport sector. The additionality criterium stipulated by the directive regarding the renewable electricity to be used means that green hydrogen that has been produced with electricity from post-support plants (such as wind power after the EEG remuneration period or hydropower) cannot be counted towards the targets within this sector. Although there is no question that hydrogen produced using electricity from post-support plants is indeed green, it is less likely that green hydrogen that does not meet the requirements of the delegated act will be in demand within this sector. The requirements of the delegated act being settled and confirmed would be one way to resolve the ongoing uncertainty surrounding the criteria that producers need to take into account. In that case, though, it is likely that certain volumes of green hydrogen would have to be used in sectors other than transport.

There is also scope for steering in relation to the European Union Emission Trading System (EU ETS). The acccountability of green synthesis products in the EU ETS would need to be clarified, though, as hydrogen-based energy carriers are currently not privileged in the EU ETS – unlike energy carriers produced from bioenergy.

If the government takes up the previously mentioned option of steering by defining different requirements for funding tools, the allocation of hydrogen is not left solely to the market. This leads to trade-offs and forces compromises to be made. Having different requirements in place can pose a challenge for hydrogen producers because they have to check in advance to confirm the sector in which they can and want to provide hydrogen, so they can plan or configure their system set-ups accordingly. This increases the level of risk for the investor and adds to their input at the implementation stage, which can hinder them during the early market ramp-up phase. Meanwhile, the government is in a position to allocate the hydrogen available to industries in which direct electrification is a challenge during a phase when hydrogen is expected to be limited.

With the focus on a market ramp-up and steering impact in the medium or even long term in certain sectors, differentiation can be the tool of choice. If the aim is to ramp up hydrogen production at a fast pace, it makes more sense to define green hydrogen in general terms that apply across all sectors, encourage the creation of trade infrastructures and leave the decision about how to use hydrogen to the market. However, such a definition of green hydrogen is not provided for in the legal framework as it stands. The delegated act to be passed on Art. 27 (3) of RED II will apply exclusively to the use of green hydrogen in the context of reducing the share of greenhouse gas emissions within the transport sector.

With a uniform definition across sectors, it would be easier for providers of green hydrogen to enter the market and their sales risk would be reduced because the market being addressed covers all sectors. Price would become the factor determining where the hydrogen would be used. A framework that is consistent across sectors would reduce the complexity, which would presumably encourage market-efficient uses for hydrogen and speed up proceedings. This approach does curtail the government's capability to steer directly, though. As a result, efficient uses for hydrogen that can only be implemented in the long term could become more challenging to roll out. Before a uniform approach could be followed, the regulatory framework would require fundamental changes and the government would have to be somewhat indifferent when it comes to the use of hydrogen.

8.3.3 Market ramp-up challenge

If Germany is to lead the way as the globally leading market and provider for hydrogen technologies over other countries focusing on innovation relating to green hydrogen and its synthesis products, the **regulations** need to be **flexible (particularly during the market entry phase)** and feasible for investors to meet with a manageable amount of effort. There are several ways of overcoming the issues that it may not be possible for the first market players to meet extremely challenging criteria directly when the market is still ramping up, that there is too much bureaucracy or that producers may turn their attention to other markets:

- While the chain of custody is being established for certification, **demonstration projects** are approved with a defined scope or time frame. Although they do not have to fulfil all the criteria at this stage, they will be able to play an important part in developing the information channels for certification (i.e. a learning system). The elements of the chain of custody and the corresponding criteria are established during these demonstration projects. They provide an opportunity to explore the criteria a green product needs to meet and the ways in which hydrogen projects, supply chains and logistics chains need to be organised. If this phase takes place within the scope of a funding mechanism like H2Global, businesses can even cover their transaction and research costs. The standard certification can be finalised once the demonstration projects have been completed. The criteria will not be changed again after that point.

- The requirements can also be intensified gradually within the context of a phase model. For example, **requirements can be shifted over time in line with the market phases**: market entry (reduced barriers to entry, minimum requirements), market ramp-up and market diffusion (e.g. full list of requirements in line with the Green Deal or certification systems). When the requirements are based on phases in this way, they should be defined clearly enough to avoid lock-in effects. The requirements that apply to individual phases need to be defined and communicated when the phase model is first introduced to avoid any uncertainty among market players.

Downsides of this model include the fact that providers might be put off by requirements that may apply later down the line (grandfathering for the first projects may help here) and that they do not have any faith in politics and are worried that the requirements could change or be made stricter at some point in the future.

- Another way of speeding up the market ramp-up is to enforce the desired criteria all along but (to start with) limit the costs to be paid or **compensate** for any **additional costs** by providing funding.

Tools to support the market have already been developed, with some flexibility built in and sustainability taken into account.

The **CertifHy certification system** is one example for the market entry phase. It is based on the definition of renewable energy set out in the RED II and a greenhouse gas reduction target of at least 60%[104] compared to hydrogen produced from natural gas using the steam methane reformation method (current reference value = 91 g CO_{2eq}/MJ). The certification period is always one year[105] and the greenhouse gas reduction target is going to be updated in future.[106]

The **competition-based H2Global** funding mechanism **with the objective of promoting the PtX market ramp-up** is another example.[107] The key concept behind H2Global is that the difference between supply prices (production and transportation) and demand prices is compensated for within the scope of a mechanism based on a contracts for difference (CfD) approach.[108] HINT.CO acts as an intermediary between the supply side and the demand side, representing both sides as a contractual partner in a double auction mechanism. On the supply side, the intermediary concludes long-term purchase agreements, assuming the price, market and contractual partner risks for the first PtX projects with the potential to be scaled to an industrial level. This gives bidding and purchasing consortia investment security and allows for the space needed to research and learn as a foundation for setting up the first supply chains and value chains. The tender process ensures that the intermediary prioritises the best price in consideration of the criteria set out previously. Tenders are used on the demand side too so as to minimise the differences in costs to be covered through the highest offers made during this

104 This is most relevant for hydrogen produced from bioenergy.
105 Cf. TÜV Süd 2021.
106 Cf. CertifHy 2022; cf. TÜV Süd 2021.
107 Cf. H2Global 2022; cf. BMWK 2021.
108 The difference is compensated for by Hydrogen Intermediary Network Company (HINT.CO) GmbH, a company founded by the not-for-profit H2Global Foundation.

process. Another key concept at the heart of the H2Global concept is the difference in the length of the terms agreed between purchase contracts and sales contracts. In other words, long-term purchase contracts on the supply side are contrasted with short-term sales contracts on the demand side. If the market prices for PtX products rise, which is to be expected as the regulatory framework evolves, the price differences to be covered will decrease accordingly. This dynamic element should improve the efficiency of the mechanism, especially in view of subsidy schemes with limited availability being used responsibly and respectfully.

As far as the funding provider is concerned, the H2Global mechanism can be controlled directly in terms of timeframe, finances and content. The term and volume are clearly limited. The German Federal Government provided initial funding of €900 million for H2Global at the end of 2021 following a first allocation decision. The first purchase agreements are scheduled for 2022, with the first deliveries expected to arrive in the EU/Germany two years later according to the current schedule.[109] The tenders start with ammonia, methanol and jet fuel, all of which are made exclusively from green hydrogen. It is expected that pure hydrogen will be added to the list. According to Art. 25 (2) of the RED II, the greenhouse gas emissions reduction for the end product must be at least 70%. In addition, the bids need to meet all the other relevant requirements stipulated in the RED II and the delegated acts. Beyond that, an environmental and social impact analysis also needs to be conducted to ensure that all production sites and the entire supply chain are considered and that the international standards (still to be defined) are met. Forced relocation and illegal land seizure are not permitted, while social and labour standards must be complied with. There is also a requirement to demonstrate how projects seeking funding contribute to local value generation, skill building and gender equality in the exporting countries and at production sites above all. Further checks verify how the project supports the implementation of the Paris Agreement and the UN Sustainable Development Goals (SDGs) in the partnering country.[110]

It still remains to be seen[111] how exactly the specific standards and criteria under H2Global will be worded and the extent to which project funding will be approved on that basis. With a view to ensuring that sufficient supply is achieved in the first tender round, it could be helpful to **just carefully select binary minimum requirements to start with**. This will avoid putting too much strain on the whole system. When funding is being allocated, the quality on offer could also become a factor alongside the price. This would allow for a qualitative comparison of how the carbon can gradually be removed from the supply chain based on the requirements that are still to be finalised as it stands.

109 Cf. BMWK 2021.
110 Cf. BMWK 2021; cf. H2Global 2022.
111 See https://www.bmwk.de/Redaktion/EN/Dossier/market-consultation-H2Global.html (last accessed: 15/07/2022).

As a result, the market entry phase could be approached more quickly and the list of requirements could be developed for later tenders under the H2Global mechanism in phases as laid out above on the basis of the experience gained during the first tender. In this case, it would be important for the **financial framework conditions to be gradually adapted in line with the market ramp-up**, with a view to avoiding any gaps in the development of a hydrogen market.

State funding will be required for as long as there are price differences to be compensated for. The government has allocated funding to H2Global over a period of ten years as it stands (1 January 2024 to 31 December 2033). If, hypothetically speaking, the status quo did not change and the price differences to be compensated for were sitting at around 25%, the current budget would allow for 1 million tonnes of ammonia or methanol to be replaced by imported green alternatives. This would amount to around 40% of the ammonia produced in Germany now or two thirds of the methanol[112]. Based on the anticipated demand for hydrogen in Germany in 2030 (90–110 terawatt hours according to the National Hydrogen Strategy set out in June 2020 as per Section 2.1), however, that percentage would drop to around 5%, making this no more than a first step (albeit an important one).

As a final point in this part of the discussion, it is important to point out that regulations on funding the transition to importing green hydrogen must be compatible with international trade law, which requires them to be **compliant with WTO regulations**. Hydrogen produced within Europe and hydrogen imported should not be treated differently and imports should not be restricted unless exceptional circumstances apply (such as those relating to environmental impact), and only if they are handled in a strictly non-discriminatory manner.

8.4 Economic challenges

In addition to regulatory certainty behind their plans, investors putting large sums of money into building up production capacity or establishing an internationally viable trade system also need a **reliable economic framework** that makes using green hydrogen a financially attractive option over other (fossil) energy carriers and thereby encourages the investments required. This applies predominantly to first movers, who have to invest in "first of its kind" systems for some of the individual transport options and know that subsequent generations of those systems are more than likely to come with cost benefits. This means there is a major risk of them not even managing to cover the costs for their products in the long term when they sell them. Regulatory documents such as purchase guarantees in the form of contracts for

112 Cf. VCI 2021.

difference – as provided by the "H2Global" funding mechanism – can provide a useful approach.

In order to establish a self-sustaining market for green hydrogen and its synthesis products in the medium to long term, costs need to be reduced on the production side. But it is just as critical that costs incurred through the use of fossil energy carriers and the associated greenhouse gas emissions are internalised more than ever before. It is important to ensure that domestic producers of green hydrogen are not structurally disadvantaged.

Since supply is always a response to the corresponding **demand for hydrogen**, specific **businesses cases** are needed for buyers of hydrogen and its synthesis products. As part of those business cases, questions to be answered include the extent to which hydrogen products should be used as raw materials and/or as energy during the early stages of the market ramp-up and whether usage should be **prioritised**, for example, on the basis of the costs (associated with avoiding greenhouse gases). For example, the willingness to pay is higher within the transport sector than within industrial settings, which could lead to hydrogen being used first and foremost in transport without any steering through criteria set out for funding tools (see Section 8.3).

A further challenge is related to the expected returns in international (energy) trade, which may be much higher than assumed here. This could lead to investments not being made in the hydrogen economy due to lower returns. The above-mentioned purchase guarantees and contracts that **minimise the risk tied to an investment** are important strands to the solution to this challenge. Only time will tell if they are sufficient on their own or if they need to be (or can be) combined with other measures.

In countries struggling with high political uncertainty, investors generally expect high risk surcharges. This has the potential to increase the price of hydrogen produced and transported by some considerable margin, making green hydrogen from those countries less attractive financially than green hydrogen from countries of origin with lower risks. If, however, a hydrogen-based partnership is still highly attractive for geopolitical or geostrategic reasons or similar, a strategy should be created with a view to making investments more secure in seemingly unstable countries, for example with the help of European financial institutions. This would make it easier to access large amounts of low-cost capital in partnering countries deemed to be high risk, which is needed to transform the energy system and produce hydrogen there.

8.5 Implementation requirements concerning the development of infrastructures in Germany

Before most of the options for importing hydrogen can be implemented in a timely fashion, major **infrastructures need to be established and/or adapted**. This development work will need to take place in the exporting countries, in Germany and possibly also in any other countries that the transport routes pass through[113]. The only exceptions are the options involving liquid synthetic hydrocarbons and methane since they can be imported via the infrastructures already in place (port terminals and pipelines with onward transportation via road and rail) without much issue at all.

For **hydrogen** to be imported **in gas form**, pipelines used to transport large volumes need to be connected to delivery terminals that can be used to transfer the hydrogen to a domestic hydrogen network that has not been developed yet. When that network is being created, domestic activities need to be **synchronised with European activities** (such as the European Hydrogen Backbone[114]) **in terms of space and time.** This involves the plans of gas grid and/or hydrogen network operators and goes hand in hand with the targeted strengthening of hydrogen demand. If the demand cannot be met initially due to insufficient infrastructures for transporting hydrogen, it may be that temporary solutions (such as container transportation by road and rail) need to be provided to guarantee a constant and reliable supply of hydrogen to end users. It is important to remember that the planning security and security of supply are two key factors potential hydrogen users consider when making decisions about investments.

For the options involving **liquid hydrogen** imports, port terminals would need to be set up so the ships could be unloaded. In addition, either a system for regasification would need to be implemented to allow for the hydrogen to go on to be distributed in gas form (as per the previous paragraph) or an infrastructure for storing and distributing liquid hydrogen would need to be introduced.

With regard to **ammonia and methanol**, significant development work would be essential on the existing infrastructures because most of the current demand for methanol and ammonia is covered using the fossil fuel natural gas directly at the processing site. They are both used almost exclusively as materials. It is very rare indeed for methanol or ammonia to be used purely

113 For example, pipelines that are not supplied directly by individual large-scale production sites will need to have feed-in or arrival points for receiving hydrogen to allow for it to be distributed on from there. It should be possible for feed-in infrastructures for liquefied natural gas, which are currently being built up to secure the energy supply in Germany and Europe, to be incorporated into a hydrogen infrastructure in the medium term.

114 The European Hydrogen Backbone initiative aims to develop a European hydrogen pipeline infrastructure, which will consist of five transport routes within the continent by 2030 according to the current plans. By 2040, the hydrogen infrastructure will span 53,000 kilometres in total, connecting 28 European countries. According to the plan, over 60% of the pipelines used by that point will be repurposed gas pipelines and the remainder will be newly constructed hydrogen pipelines (cf. EHB 2022).

as energy carriers. Bearing in mind the target to remove the fossil fuel element from chemical raw materials, the use of renewable ammonia or methanol as a material after it is imported would require the processes in integrated chemical plants to be adapted accordingly. This is because both raw materials would subsequently be supplied externally, meaning they would no longer be part of the process chain on site as is the case when fossil-based ammonia or methanol is used. For example, the loss of the process heat usually released by exothermic formation reactions would need to be compensated for in some way. It would also be necessary to rethink the supply of CO_2 required for the likes of urea production. Finally, additional costs could be incurred if the storage capacity needs to be expanded.

In the event that hydrogen is imported using **hydrogen carriers** (such as LOHC or ammonia), the required distribution infrastructures would need to be developed initially and/or existing infrastructures would need to be repurposed accordingly. For the LOHC option, the carrier material would also need to be returned to allow for repeated usage. Depending on the exact circumstances, the same distribution systems could be used (transportation by container) or special dedicated systems could be required (transportation by pipe).

9 Conclusions

Developing a green hydrogen economy in Germany is a challenging endeavour and a pressing matter if Germany is to meet its target of achieving climate neutrality by 2045. Given the short space of time available for this process, it is essential that many different stakeholders from politics, industry and society **work closely together and take concerted action**, **consistently make progress** and adopt a supportive attitude towards implementation.

9.1 Transition into the green hydrogen economy by 2030

Forecasts suggest that the **domestic demand** for hydrogen and its synthesis products in Germany will be between 45 and 100 terawatt hours in 2030 and between 400 and 700 terawatt hours in 2045. Based on the current situation, a large proportion of that demand will need to be imported from the EU and probably even countries outside of the EU (see Section 2.1).

It is evident, not least from the quantities derived from calculations (see Section 4) – which still represent the lower range of the demand stipulated for 2030 – that the **expansion goals** and especially the volumes of renewable energy required to achieve them are **ambitious**. Assuming that an exporting country manages to install renewable energy systems with an output of 35 gigawatts (17.5 gigawatts of photovoltaic power and 17.5 gigawatts of onshore wind power)[115] for producing electricity by 2030, the calculations[116] suggest that it would be possible to produce around 50 terawatt hours of hydrogen and transport it to Germany by pipeline provided that the circumstances would allow a pipeline to be constructed. If synthesis products were also produced using hydrogen from electrolysis in the country of origin and subsequently shipped to Germany[117], the lower energy efficiency would mean that around 40 terawatt hours of ammonia, 32 terawatt hours of methanol or 28 terawatt hours of Fischer-Tropsch products would be able to be used as materials. Looking at the transport options that are not expected to be available until after 2030, the LOHC option would allow for around 34 terawatt

115 This equates to around 35% of the photovoltaic and onshore wind power systems that were installed in Germany in 2019 (cf. BMWi 2020a, page 15).
116 Refer to the reference material for the generic production potential assumed (2,500 full-load hours combined) (Schmidt et al. 2022).
117 In the example, a distance of 10,000 kilometres was assumed as standard to allow for a comparison between the volumes being transported.

hours of hydrogen to be imported by ship, starting with that same original output of 35 gigawatts of renewable electricity. Ammonia as a hydrogen carrier and liquid hydrogen also being transported by ship would be slightly above that with around 38 terawatt hours.

This analysis paper reveals that the corresponding volumes can be imported in principle, provided that the relevant requirements surrounding infrastructure, regulatory and business frameworks are met. But effective action needs to be taken to **lay the foundations** now. It may be true that green hydrogen will not be used in large volumes until after 2030, but progress needs to be made sooner rather than later in the **transition to climate-neutral production processes**, within the chemical, steel, glass industry and beyond, and **transport routes with zero CO_2 emissions** for heavy-duty lorries, ships and planes. Otherwise, the future of a self-sustaining market for green hydrogen to meet the demand in Germany is not a realistic vision. This future depends on sufficient volumes of electricity produced from renewable sources being available in exporting regions, electrolysers being installed and initial import infrastructures, storage facilities and distribution chains for green hydrogen being set up between exporting and importing countries.

For a successful **market ramp-up** it is mandatory to move from show cases in the form of initial pilot or demonstration projects to functioning **business cases**. Given the volumes of hydrogen required to make importing a financially viable option, the technology needs to be scaled up – a process that has already begun for electrolysers – and **industrial series production** needs to be introduced. The current scale of production for some of the key technologies will not be able to keep up with the constantly rising demand for climate-neutral hydrogen and its synthesis products and will not allow for international supply chains to be established on a commercial scale. Alongside electrolysers, other systems required to produce hydrogen include synthesis systems for producing synthetic hydrocarbons and direct air capture systems for sourcing the additional carbon required. Progress also needs to be made on scaling up LOHC technology or improving ammonia crackers that are relied upon when hydrogen is transported using hydrogen carriers.

The availability of infrastructures for receiving and distributing hydrogen in Germany is also an important factor in completing international supply chains. **Ports** for receiving imported hydrogen and synthesis products need to be developed and/or expanded, while **storage facilities**, **logistics chains** and **distribution** pipeline systems need to be established. Due to the European links within the energy and industrial sector, these infrastructures cannot be limited to Germany and instead will have to be **incorporated into the European network**. For example, pipelines would need to be included as part of the European Hydrogen Backbone initiative. During the initial phase between now and 2030, one major challenge will be to strategically develop regional growth clusters in line with growing demand going forward and intertwine them with the electricity and hydrogen infrastructures of the other EU member states.

Other political and economic goals need to be considered in relation to the transition into a hydrogen economy by 2030 too, including funding for mutually beneficial development partnerships that have already been set up or are due to be set up and the diversification of sources to improve the security of supply. On the subject of security of supply, Russia's war against Ukraine is adding considerably to the uncertainty that already goes hand in hand with concrete plans to restructure the energy (transportation) infrastructures. Before the invasion, available capacity in pipelines that transport gas from Eastern Europe to Germany and other European countries had the potential to be repurposed for hydrogen. This option is no longer available in the short to medium term in light of the political situation. Equally, there is little more available capacity in Western Europe because gas deliveries had to be shifted to these areas of the grid at short notice and any spare capacity had to start being drawn on to import more LNG. Within this context, it is recommended that one-sided supply relationships are avoided at all costs when hydrogen partnerships are being formed. The key to improving the security of supply is ensuring that partnerships are mutually beneficial and built on an equal footing – combined with the diversification of sources. This could reduce the risks of shortages and withdrawal, which would involve a negative development for both partners.

9.2 Import options for the transition into the green hydrogen economy by 2030

Following the analysis of various transport options for importing hydrogen and its synthesis products into Germany[118], **there is not one transport option that emerges as a clear frontrunner**. All of the alternatives considered have their own strengths and weaknesses, as well as different times and requirements for implementation. This means that different transport options should be selected on a **case-by-case and application-by-application basis**, with the expectation that a wider range of options can only help to **diversify** the sources being relied upon. Some transport options appear to be more suitable for a fast transition into the green hydrogen economy, however, on the basis of efficiency and cost factors. A distinction has to be made between **use as a material** and **use as energy**, the use of specific **synthesis products** and the use of **hydrogen carrier media**.

118 The analysis follows a terminal-to-terminal approach which analyses the transportation of hydrogen and its synthesis products from the exporting country to the importing country. Transportation by ship and pipeline over long distances is explored. The infrastructure also required to distribute the products within Germany does not directly form part of the analysis.

The transition towards **importing renewable ammonia as a raw material** (for use in the chemical industry in particular) that has been produced using green hydrogen and transported by ship **could begin immediately** and this option could be implemented within around two years. In this case, ammonia made with renewable energy could remove the need to import standard ammonia or replace some of the ammonia produced domestically. The entire production and transport chain has already been developed on an industrial scale. Ammonia produced with hydrogen sourced from electrolysis could also prove to be financially competitive relatively quickly (at a CO_2 price of around €100 per tonne) (see Sections 4 and 6).[119] Since only around 22% of the ammonia required in Germany is imported as it stands[120], the existing import infrastructures would need to be extended considerably if ammonia was to be imported into Germany in large volumes in future.

When it comes to the transition towards **importing pure hydrogen**, transporting gaseous hydrogen **by pipeline** appears to be a particularly suitable solution. If existing natural gas pipelines could be repurposed and that work was started today, it could potentially be possible to be transporting a significant volume of hydrogen to Germany within around 3 to 5 years, provided that planning and implementation were efficient and the capacity for producing renewable energy in the country of origin could be built upon as required at the same time. Given that 8 to 10 years is the timeframe anticipated for constructing new pipelines, the focus should be on repurposing individual pipelines that are already in place or building onto existing routes to ensure that the transition towards hydrogen imports can be made as efficiently as possible. More in-depth analysis is required for implementation opportunities to be assessed, including geographical details, available capacity and geopolitical framework conditions. Beyond the implementation considerations, another benefit of using hydrogen pipelines to transport pure hydrogen is that it is the most **cost-effective** of all the options considered when distances of up to 4,000 kilometres are being covered. Plus, the hydrogen can be used either as a material or as energy across all sectors once it has been transported. When hydrogen is transported by pipeline, there are no concerns about **purity** and the **efficiency level is higher** than with all the other options, which means that the most energy can be used in Germany (measured against the electricity input in the exporting country).

The challenge here, though, is ensuring the **utilisation** of a sufficiently large and thus cost-effective **pipeline**(see Section 6). This does not just rely on enough hydrogen being supplied – it is also essential that the corresponding **capacity for producing enough renewable electricity** to produce the hydrogen in the first place is installed in the exporting country. For example, with a pipeline with a diameter of around 1,000 millimetres and the capacity to

119 With production costs of under €3 per kilogram of hydrogen (see Section 3.5.3).
120 See Sections 5.2 and 6.

transport 6,000 to 7,000 tonnes of hydrogen every day, around 50 terawatt hours of hydrogen could be transported annually.[121] Around 85 terawatt hours of electricity would need to be made available in the exporting country to produce that hydrogen. That equates to a combined wind power and photovoltaic system output of around 35 gigawatts.[122] To put this into context, using a pipeline of this size between the Iberian Peninsula and Germany to capacity would require almost the entire capacity of wind and photovoltaic systems that were installed in Spain in 2020 (approximately 40 gigawatts)[123,124].

Importing green methanol and products of Fischer-Tropsch synthesis for use as materials are **further transport options that could be implemented quickly for limited volumes**. The implementation time would be around two years, provided that enough CO_2 could be sourced from unavoidable industrial point sources and used for the synthesis process. In that case, the implementation time would be roughly on a par with the ammonia option and shorter than the time required to implement the option of repurposing existing pipelines for hydrogen. Both transport options are associated with higher costs than importing ammonia by ship and hydrogen by pipeline, however (see Section 4). Synthetically produced methanol could provide a financially attractive alternative to methanol produced in the conventional way using natural gas before 2030 with CO_2 at a price of around €200 per tonne. Meanwhile, Fischer-Tropsch products are likely to remain much more expensive than their counterparts produced from fossil fuels – even in the long term. But they will be required before 2030 so that blending mandates can be met (for kerosene, for instance).

Methanol and Fischer-Tropsch products are fully **compatible** with the current applications and uses, meaning they could provide direct replacements for methanol produced in the conventional way and Fischer-Tropsch products based on crude oil. Existing **means of transport and industrial systems could continue to be used** without the need to make any major adjustments. However, to meet climate neutrality requirements in the medium term, the production of synthetic hydrocarbons needs to gradually be transitioned so that sustainable sources of CO_2 are used. **Direct air capture** is certainly an option here albeit one that is not expected to be available on an industrial scale and with competitive conditions by 2030. If climate targets are to be met and the lack of financial incentives encouraging this kind of transition is to be

121 The pipeline has been assumed to be used at 60% of its full capacity to account for a volatile feed-in from the renewable energy systems. If the pipeline were used at full capacity, the costs would increase because storage facilities would then also be required in the exporting country.

122 With an average of 2,500 full-load hours assumed for the renewable energy systems. Some of the energy produced would have to be curtailed (around 10%) to ensure the most cost-effective set-up.

123 Cf. IRENA 2021.

124 Even a small pipeline with the capacity to transport around 5 terawatt hours of hydrogen each year (which would be less attractive from a financial perspective) would need around 10 terawatt hours of electricity, equating to a system capacity output of around 4 gigawatts in the exporting country.

compensated for, clear corresponding legal regulations are required to **avoid any fossil fuel lock-in effects**.

Based on the analysis of the **remaining transport options** that could potentially be used to import hydrogen and its synthesis products into Germany **by 2030**, it can be assumed that they will not be able to make a relevant contribution to meeting the demand in time. The use of ammonia as energy is one possible exception. If machinery that can use ammonia directly as an energy carrier is available and put to use on an industrial scale, the scope of the option of transporting ammonia by ship could be extended accordingly beyond the use as material explored in this analysis paper.

Transporting **liquid hydrogen by ship** is also an option for importing hydrogen from countries outside of Europe **in the medium to long term**. This makes most economic sense when the distance to be covered exceeds 8,000 kilometres. One major benefit of transportation by ship is that the distance has very little impact on the energy losses and overall costs associated with hydrogen imports. The hydrogen tankers required for this option are still being developed and the landing terminals are far from being implemented at ports, however. On that basis, this is considered to be a medium-term option at best, meaning that it will not be available on a large enough scale until after 2030.

9.3 Transition technologies and shifts in value creation

Due to the limited supply of hydrogen and the need to establish the infrastructures for its production and transportation at this stage, there is no doubt that it will only be possible to introduce climate-neutral alternatives to some of the processes within the energy sector and industrial production processes by 2030. Since it is not possible to transition away from the use of energy based on fossil fuels immediately, **temporary solutions** are required in the meantime. With that in mind, it is important that investments into the hydrogen economy are encouraged between now and 2030 but also that investments that cannot be climate-neutral to start with have the potential to be transitioned at a later stage (“H_2-ready”). Plausible phase-out plans must be drawn up for systems that need to be operated with fossil energy carriers initially, with a view to ensuring that climate targets can be met.

Generally speaking, the pathway to the green hydrogen economy can follow a logical sequence based on the supply and demand of green hydrogen. With a view to boosting the rise of the green hydrogen economy and achieving climate targets, strategic investments can also be made to help increase the demand. One example would be to introduce the direct reduction of iron ore using hydrogen within the steel sector. This could, however, mean that the available supply of green hydrogen does not always cover the need for hydrogen within the value or logistics chains that have already undergone the transition by 2030. In this case, it may be necessary to also use hydrogen produced from fossil fuels for a transition period in the interests of security of supply. It is therefore basically irrelevant whether the transport options considered in this analysis paper are used to transport hydrogen produced from natural gas (grey hydrogen), hydrogen produced from natural gas with captured carbon dioxide (blue hydrogen) or hydrogen produced by electrolysis using renewable electricity (green hydrogen).

As capacity is freed up when it is no longer needed to produce synthesis products based on fossil fuels, the opportunity may arise to use it to support the rise of a green hydrogen economy. **One option for a "grey hydrogen bridge"** of this nature could be to repurpose existing systems previously used to produce ammonia and methanol in Germany and to use them instead to produce grey hydrogen. As it stands, ammonia and methanol are usually produced on site in Germany using hydrogen from steam methane reformers. In other words, they are produced in close proximity to where they are going to be used. Ammonia and methanol produced domestically could gradually be replaced by imported green synthesis products. The steam methane reformers would be freed up and could be used to produce grey hydrogen that could be used elsewhere – in the event of gaps in supply as described above, for example. In some cases, this could also reduce the risk of stranded assets. In this scenario, ramping up imports of renewable ammonia and methanol would not only save on CO_2. It would also **bring forward the rise of the green hydrogen economy** by making it easier to switch to processes based on hydrogen while improving the security of supply. Local hydrogen distribution networks developed in this scenario would then ideally also be used for green hydrogen later down the line.

As the transition is made to a climate-neutral economy and energy supply, **value chains** are bound to change and shift in the process. The analysis of the transport options reveals that the production of synthesis products in the exporting country can be much more efficient and cost-effective than importing hydrogen produced by electrolysis and performing the synthesis process after it has arrived in Germany when certain conditions apply, such as very low production costs for renewable energy and low-cost, easy-access sources of CO_2. There is a chance of **losing out on value creation in Germany** in relation to the production of ammonia and fertilisers if businesses decide to move to locations set up for this specifically. The question of whether, and if so in which circumstances, it might be more cost-effective to perform the synthesis process in Germany than to import the energy carriers directly depends largely on how the costs associated with technology and raw materials evolve (see Section 4) along with other factors. This requires careful consideration on a case-by-case basis.

9.4 Flexible political steering and cooperation within Europe and worldwide

Achieving the transition into the green hydrogen economy by 2030 is an ambitious goal in its own right. But the fact that the foundations need to be laid for the period up to 2045 in this time too means that it is essential for the **long-term vision to be combined with an ambitious transition**.

Political decision-makers are called upon to work with businesses, infrastructure operators and regulators, and the general public to formulate clear targets and interim goals and create funding mechanisms so that industry stakeholders **have no doubt about what needs to be achieved** through the processes to be introduced and can draw on guidance and support along the way. It is **also** essential for enough **flexibility** to be maintained to allow for fast implementation. A certain sensibility is also required towards any negative environmental and social impact of hydrogen projects and (newly emerging) dependencies on suppliers. This involves paying close attention to the global race for climate-neutral hydrogen and technological leadership as well as maintaining a clear picture of domestic value creation. The criteria for requirements under political support and funding schemes should not be too strict during the initial phase up to the year 2030 to avoid it becoming unnecessarily challenging to make investments in green hydrogen supplies. This appears to be highly relevant in view of the different objectives set out in the National Hydrogen Strategy, which include contributing to achieving climate goals, ensuring the long-term future of Germany as a technological centre, initiating market ramp-up of the technology and creating a policy framework[125].

Many aspects of the hydrogen economy still need to take shape. Taking transportation as an example, it is still not certain which transport routes will be used and which format hydrogen will be in when it is imported into Germany – gas, liquid and/or absorbed by a carrier. When the political and regulatory framework is being created, strategic decisions are being made and demand planning is being performed, mechanisms need to be strategically introduced at the political level to **allow some political flexibility for amendments** if required. This could come in the form of phased models for funding criteria (see Section 8.3), defined target ranges or regular review loops. In this respect, all stakeholders from politics, industry and society need to be **ready to respond with flexibility**. Changes made specifically on the basis of **joint learning processes** should not be viewed as uncoordinated activities. In view of the prevailing uncertainty, they should instead be seen as part of the ongoing development and optimisation of implementation mechanisms required to establish the widespread supply of green hydrogen.

125 Cf. BMWi 2020b, page 5 ff.

Making the transition from fossil fuels to a climate-neutral energy supply opens up an opportunity to break free from existing energy dependencies. This paves the way for new or updated partnerships aimed at **diversifying the energy supply and improving the security of that supply**. Alongside the option of recalibration, which is inherent in change processes as a general rule, the **wider range of potential exporting countries** is important when it comes to **renewable energy** and green hydrogen. Unlike fossil fuel resources, which are restricted in their location, renewable electricity can be produced from wind and photovoltaic power more or less anywhere, although the production costs will vary based on location. A country looking to export green hydrogen or its synthesis products will be able to compete internationally if it is in a position to offer favourable production costs for renewable electricity, sufficient water resources and, if hydrocarbons are being exported, CO_2 sources. When it comes to securing the water supply, desalination plants on the coast offer such flexibility, as long as renewable electricity can be produced cost-effectively and the brine by-product can be disposed of in an environmentally friendly way. In the long run, direct air capture technology could be the best way to source the carbon required.

Ultimately, **hydrogen can be so much more than** just an **energy carrier and raw material**. A properly developed and sustainable hydrogen economy will be able to have a lasting **impact on policies surrounding the environment, industry and development**. For example, the creation of a hydrogen infrastructure that crosses European borders has the potential to improve cohesion within the European Economic Area and strengthen the continent's energy system. For Germany, the only way to meet the demand for green hydrogen is to supplement domestic production with imports. Diversified imports from countries within the EU and further afield avoids one-sided dependencies on suppliers and also opens up opportunities on new markets for technologies and services provided by German businesses. There is also scope for emerging and developing countries to benefit by getting heavily involved in value chains. Developing a secure, climate-neutral energy supply in these countries will also contribute to achieve the global climate targets. Thereby it is absolutely essential for **partnerships to be established on an equal footing** for international projects so that **all parties can reap the benefits**. This relies on the creation of a transparent, non-discriminatory European and international regulatory framework for the green hydrogen economy, including the relevant criteria for certification and imports, guarantees of origin and traceable process chains – none of which should make it any more difficult than it needs to be to ensure a swift and speedy market ramp-up. The right balance needs to be struck here once again.

Literature

acatech 2022
HySupply: German-Australian Feasibility Study of Hydrogen produced from Renewables, 2020. URL: https://en.acatech.de/project/hysupply-german-australian-feasibility-study-of-hydrogen-produced-from-renewables/ [Stand: 09.08.2023].

Agora Energiewende 2020
Agora *Energiewende: Klimaneutrale Industrie - Schlüsseltechnologien und Politikoptionen für Stahl, Chemie und Zement*, 2020. URL: https://static.agora-energiewende.de/fileadmin/Projekte/2018/Dekarbonisierung_Industrie/164_A-EW_Klimaneutrale-Industrie_Studie_WEB.pdf [Stand 15.07.2022].

Amnesty International 2022
Amnesty International Report 2021/22: *The State of the world's human rights*, 2022. URL: https://www.amnesty.org/en/documents/pol10/4870/2022/en/ [Stand: 15.07.2022].

Ariadne 2021a
Kopernikus-Projekt Ariadne Potsdam-Institut für Klimafolgenforschung (PIK): *Deutschland auf dem Weg zur Klimaneutralität 2045 - Szenarien und Pfade im Modellvergleich,* 2021. URL: https://ariadneprojekt.de/publikation/deutschland-auf-dem-weg-zur-klimaneutralitat-2045-szenarienreport/ [Stand: 15.07.2022].

Ariadne 2021c
Ueckerdt, F./ Pfluger, B. / Odenweller, A. / Günther, C. / Knodt, M. /Kemmerzell, J. / Rehfeldt, M. / Bauer, C. / Verpoort, P. / Gils, H. / Luderer, G et al. 2021: Ariadne Kurzdosier: *Durchstarten trotz Unsicherheiten: Eckpunkte einer anpassungsfähigen Wasserstoffstrategie,* 2021. URL: https://www.kopernikus-projekte.de/lw_resource/datapool/systemfiles/cbox/1835/live/lw_datei/ariadne_kurzdossier_wasserstoff_november2021.pdf [Status: 15.07.2022].

Ariadne 2022
Kopernikus-Projekt Ariadne Potsdam-Institut für Klimafolgenforschung (PIK): Securing hydrogen imports for Germany: Import needs, risks and strategies on the way to climate neutrality, 2022. URL: https://www.kopernikus-projekte.de/lw_resource/datapool/systemfiles/cbox/1963/live/lw_datei/ariadne-analysis_securing-hydrogen-imports_february2022.pdf [Status: 09.08.2023].

BAFA o.J.
Bundesamt für Wirtschaft und Ausfuhrkontrolle: *Rohölstatistik in der Bundesrepublik Deutschland, o.J.* URL: https://www.bafa.de/DE/Energie/Rohstoffe/Rohoel/rohoel_node.html [Status: 15.07.2022].

BAFA 2022
Bundesamt für Wirtschaft und Ausfuhrkontrolle: *Erdgasstatistik,* 2022. URL: https://www.bafa.de/DE/Energie/Rohstoffe/Erdgasstatistik/erdgas_node.html [Status 15.07.2022].

BDEW 2019
Bundesverband der Energie- und Wasserwirtschaft e.V.: *Zahl der Woche / 954 Mrd. kWh Erdgas*, 2019. URL: https://www.bdew.de/presse/presseinformationen/zahl-der-woche-erdgasverbrauch-945-mrd-kwh/ [Status: 15.07.2022].

BDI 2021
Bundesverband der Deutschen Industrie e.V.: Klimapfade 2.0 – Ein Wirtschaftsprogramm für Klima und Zukunft, 2021. URL: https://bdi.eu/artikel/news/klimapfade-2-0-ein-wirtschaftsprogramm-fuer-klima-und-zukunft/ [Status: 15.07.2022].

BMWi 2020a
Bundesministerium für Wirtschaft und Energie: *Erneuerbare Energien in Zahlen. Nationale und Internationale Entwicklung im Jahr 2019*, 2020. URL: https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/erneuerbare-energien-in-zahlen-2019.pdf?__blob=publicationFile&v=6 [Status: 15.07.2022].

BMWi 2020b
Bundesministerium für Wirtschaft und Energie: The National Hydrogen Strategy, 2020. URL: https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=1 [Status: 09.08.2023].

BMWi / WV Stahl/ IG Metall 2021
Bundesministerium für Wirtschaft und Energie/Wirtschaftsvereinigung Stahl/Industriegewerkschaft Metall: *Stand der Gespräche zum Handlungskonzept Stahl zwischen dem Bundeswirtschaftsministerium und der Stahlindustrie in Deutschland*, 2021. URL: https://www.stahl-online.de/wp-content/uploads/2021-05-12-stahl-erklaerung.pdf [Status: 15.07.2022].

BMWK 2019
Bundesministerium für Wirtschaft und Klimaschutz: *Dialogprozess Gas 2030 – Erste Bilanz –*, 2019. URL: https://www.bmwk.de/Redaktion/DE/Downloads/C-D/dialogprozess-gas-2030-erste-bilanz.html [Status: 15.07.2022].

BMWK 2021
Bundesministerium für Wirtschaft und Klimaschutz: *„Wasserstoff: Schlüsselelemente für die Energiewende"*, 2021. URL: https://www.bmwk.de/Redaktion/DE/Dossier/wasserstoff.html [Status: 15.07.2022].

Bundesregierung 2021
Die Bundesregierung: *PtL-Roadmap; Nachhaltige strombasierte Kraftstoffe für den Luftverkehr in Deutschland,* 2021. URL: https://www.bmvi.de/SharedDocs/DE/Anlage/LF/ptl-roadmap.pdf?__blob=publicationFile [Status: 15.07.2022].

CertifHy 2022
CertifHy: *Certification Schemes*, 2022. URL: https://www.certifhy.eu/go-definition/ [Status: 15.07.2022].

Climeworks 2022
Climeworks Website,2022. URL: https://climeworks.com [Status: 15.07.2022].

dena 2021
Deutsche Energie-Agentur GmbH: *dena-Leitstudie Aufbruch Klimaneutralität,* 2021. URL: https://www.dena.de/newsroom/publikationsdetailansicht/pub/abschlussbericht-dena-leitstudie-aufbruch-klimaneutralitaet/ [Status: 15.07.2022].

Der Standard 2022
Wandler, R.: *Spanien vollzieht in Sachen Westsahara eine Kehrtwende*, 2022. URL: https://www.derstandard.de/story/2000134286864/spaniens-vollzieht-in-sachen-westsahara-eine-kehrtwende [Status: 15.07.2022].

Destatis 2022a
Statistisches Bundesamt (Destatis): *Produktionswert, -menge, -gewicht und Unternehmen der Vierteljährlichen Produktionserhebung: Deutschland, Jahre, Güterverzeichnis (9-Steller)*, Genesis Online, Tabelle 42131-0003, 2022. URL: https://www-genesis.destatis.de/genesis/online [Status: 15.07.2022].

Destatis 2022b
Statistisches Bundesamt (Destatis): *Aus- und Einfuhr (Außenhandel): Deutschland, Jahre, Warenverzeichnis (8-Steller)*, Genesis Online, Tabelle 51000-0013, 2022. URL: https://www-genesis.destatis.de/genesis/online [Status: 15.07.2022].

Deutscher Bundestag 2020
Deutscher Bundestag: *Erklärung zur Lage der Menschenrechte in Saudi-Arabien aus Anlass des G20-Gipfels vom 18. November 2020*, 2020. URL: https://www.bundestag.de/webarchiv/Ausschuesse/ausschuesse19/a17_menschenrechte/Erklaerungen/saudi-arabien-807140 [Status: 15.07.2022].

EHB 2022
Van Rossum,R./Jens, J./La Guardia, G./Wang, A./Kühnen, L./Overgaag, M.: *A European Hydrogen Infrastructure Vision Covering 28 Countries*, 2022. URL: https://gasforclimate2050.eu/wp-content/uploads/2022/04/EHB-A-European-hydrogen-infrastructure-vision-covering-28-countries.pdf [Status: 15.07.2022].

El Pais 2021
El Pais: *Why the closure of an Algerian gas pipeline is bad news for Spain*, 2021. URL: https://english.elpais.com/economy-and-business/2021-10-28/why-the-closure-of-an-algerian-gas-pipeline-is-bad-news-for-spain.html [Status: 15.07.2022].

Elten et al. 2021
Elten, E./Durisin, M.: *„Fertilizer Prices Are Getting More Expensive in Europe, Adding to Food-Inflation Concerns"*. In: Bloomberg, 2021 URL: https://www.bloomberg.com/news/articles/2021-10-29/european-fertilizer-prices-set-to-surge-amid-energy-squeeze [Status 15.07.2022].

Energate GmbH 2021
Energate Messenger+: RWE carries out large-scale tests on hydrogen turbine in Lingen , 2021. URL: https://www.energate-messenger.com/news/218404/rwe-carries-out-large-scale-tests-on-hydrogen-turbine-in-lingen [Status: 09.08.2023].

ESKP o.J.
Earth System Knowledge Platform – die Wissensplattform des Forschungsbereichs Erde und Umwelt der Helmholtz-Gemeinschaft: *„Wasserstoff: ein geeigneter umweltfreundlicher Energieträger?"*, o.J. URL: https://www.eskp.de/schadstoffe/wasserstoff-ein-geeigneter-umweltfreundlicher-energietraeger-935484/ [Status: 15.07.2022].

European Commission 2020
European Commission: *A hydrogen strategy for a climate-neutral Europe, COM (2020)* 301 final, 2020. URL: https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf [Status: 15.07.2022].

European Parliament 2021
European Parliament: *Question for Written Answer E-005456/2021 to the Commission*, Subject: Algerias Decision on Supply of Gas, 2021. URL: https://www.europarl.europa.eu/doceo/document/E-9-2021-005456_EN.html [Status: 15.07.2022].

Fasihi/Breyer 2020
Fasihi, M./Breyer, Ch.: *Baseload electricity and hydrogen supply based on hybrid PV-wind power plants; Journal of Cleaner Production, Volume 243, 2020*. URL: https://www.sciencedirect.com/science/article/pii/S0959652619333360?via%3Dihub [Status: 15.07.2022].

Fasihi et al. 2019
Fasihi, M./Efimova, O./Breyer, C.: *Techno-economic assessment of CO_2 direct air capture plants,* 2019. URL: https://www.sciencedirect.com/science/article/pii/S0959652619307772 [Status: 15.07.2022].

Fraunhofer ISE 2021
Fraunhofer Institute for Solar Energy Systems ISE: *Cost Forecast for Low Temperature Electrolysis – Technology Driven Bottom-Up Prognosis for PEM and Alkaline Water Electrolysis Systems*, 2021. URL: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/cost-forecast-for-low-temperature-electrolysis.pdf [Status: 15.07.2022].

Fraunhofer ISI 2013
Fleiter, T./ Schlomann, B./ Eichhammer, W.: *Energieverbrauch und CO_2-Emissionen industrieller Prozesstechnologien – Einsparpotentiale, Hemmnisse und Instrumente*, 2013. URL: https://www.isi.fraunhofer.de/content/dam/isi/dokumente/ccx/2013/Umweltforschungsplan_FKZ-370946130.pdf [Status: 15.07.2022].

Fraunhofer ISI 2020
Wietschel, M./Bekk, A./Breitschopf, B./Boie, I./Edler, J./Eichhammer, W./Klobasa, M./ Marscheider-Weidemann, M./Plötz, P./Sensfuß, F./Thorpe, D./Walz, R.: *Chancen und Herausforderungen beim Import von grünem Wasserstoff und Syntheseprodukten, Policy-Brief 03/2020*. URL: https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2020/policy_brief_wasserstoff.pdf [Status: 15.07.2022].

H2Global 2022
H2Global Stiftung: Bollerhey, T./ Exenberger, M./ Geyer, F./ Westphal, K.: *H2Global - Idea, Instrument and Intentions*, Policy Brief 01/2022, 2022 *(im Erscheinen)*. https://files.h2-global.de/H2Global-Stiftung-Policy-Brief-01_2022-EN.pdf [Status: 09.08.2023]

HESC 2022
Hydrogen Energy Supply Chain (HESC) *Website*, 2022. URL: https://www.hydrogenenergysupplychain.com/about-hesc/ [Status: 15.07.2022].

Human Rights Watch 2022
Human Rights Watch: World Report 2022, *Events of 2021,* 2022. URL: https://www.hrw.org/sites/default/files/media_2022/01/World%20Report%202022%20web%20pdf_0.pdf [Status: 15.07.2022].

HySTOC 2019
Hydrogen Supply and Transportation Using Liquid Organic Hydrogen Carriers (HYSTOC): *D8.4 LOHC production cost estimation study*, 2019. URL: https://ec.europa.eu/research/participants/documents/downloadPublic/Ry9BYnVIZzQrNitsbTZBNDJOOE91czNVbEJ2VmxZQ2hocmVSOEFtSkMyNmtJQ0haYnRoV3R3PT0=/attachment/VFEyQTQ4M3ptUWZJbUlVSlNDNlhONkV6OWxYc0h3YjY= [Status: 15.07.2022].

IEA 2021a
International Energy Agency: *Ammonia technology Roadmap. Towards more sustainable nitrogen fertiliser production*, 2021. URL: https://iea.blob.core.windows.net/assets/6ee41bb9-8e81-4b64-8701-2acc064ff6e4/AmmoniaTechnologyRoadmap.pdf [Status: 15.07.2022].

IEA 2021b
International Energy Agency: *Global Hydrogen Review*, 2021. URL: https://www.iea.org/reports/global-hydrogen-review-2021 [Status: 15.07.2022].

IKEM 2021
Kalis, M. / Langenhorst, T. / Harsch, V. et al.: *Kurzgutachten Anrechenbarkeit, Zertifizierung und internationaler Handel von grünem Wasserstoff,* 2021. URL: https://energiesysteme-zukunft.de/fileadmin/user_upload/Veranstaltungen/Verschiedene/20210712_IKEM-Gutachten_Wasserstoffregulatorik-1.pdf [Status 15.07.2022].

IRENA 2018
International Renewable Energy Agency: *Energy Profile Brazil,* 2018. URL: https://www.irena.org/IRENADocuments/Statistical_Profiles/South%20America/Brazil_South%20America_RE_SP.pdf [Status: 15.07.2022].

IRENA 2021
International Renewable Energy Agency: *Renewable Capacity Statistics* 2021. URL: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Apr/IRENA_RE_Capacity_Statistics_2021.pdf [Status: 15.07.2022].

IWR 2021
Internationales Wirtschaftsforum Regenerative Energien (IWR): *Saudi-Arabien baut eines der weltgrößten Solarkraftwerke,* 2021. URL: https://www.iwr.de/news/saudi-arabien-baut-eines-der-weltgroessten-solarkraftwerke-news37350 [Status: 15.07.2022].

IVA 2020
Industrieverband Agrar (IVA): Wichtige Zahlen – Düngemittel – Produktion - Markt - Landwirtschaft, 2020. URL: https://www.iva.de/publikationen/wichtige-zahlen-2019-2020 [Status: 15.07.2022].

Karstens/ Levin 2010
Karstens, U./Levin, I.: *Molekularer Wasserstoff in der Atmosphäre – Untersuchung der Quellen- und Senkenprozesse mit einem Regionalmodell*, 2010. URL: https://meetingorganizer.copernicus.org/DACH2010/DACH2010-47.pdf [Stand: 15.07.2022].

Kawasaki 2019
Kawasaki Heavy Industries, Ltd.: *Japan's Movement for Hydrogen Society and Global Hydrogen Supply Chain,* 2019. URL: https://www.sintef.no/globalassets/project/hyper/presentations-day-1/day1_1510_taira_kawasakihi.pdf [Stand: 15.07.2022].

KIT 2020
Heß, D./Klumpp, M./Dittmeyer, R.: *Nutzung von CO_2 aus Luft als Rohstoff für synthetische Kraftstoffe und Chemikalien,* 2020. URL: https://vm.baden-wuerttemberg.de/fileadmin/redaktion/m-mvi/intern/Dateien/PDF/29-01-2021-DAC-Studie.pdf [Status: 15.07.2022].

Kölling 2021
Kölling, M.: *Ammoniak als Öko-Brennstoff für Kraftwerke*. In: Heise.de - MIT Technology Review. 01.04.2021. URL: https://www.heise.de/hintergrund/Ammoniak-als-Oeko-Brennstoff-fuer-Kraftwerke-5999498.html [Status: 15.07.2022].

Methanex 2020
Methanex: *Methanol – Sicherheitsdatenblatt gemäß Verordnung (EG) Nr. 1907/2006 (REACH) in jeweils geänderter Fassung*, 2020. URL: https://www.methanex.com/sites/default/files/safety/SDS-2014/Europe-REACH/Methanol-EU_DE_eSDS_07.23.2020.pdf [Status: 15.07.2022].

Methanex 2022
Methanex: *Historical Methanex Posted Price*, 2022. URL: https://www.methanex.com/our-business/pricing [Status: 15.07.2022].

NWR 2021
Nationaler Wasserstoffrat (Hrsg.): *Hydrogen Action Plan Germany 2021-2025*, 2021. URL: https://www.wasserstoffrat.de/fileadmin/wasserstoffrat/media/Dokumente/EN/2021-07-02_NWR-Hydrogen_Action_Plan.pdf [Status: 09.08.2023].

OHCR 2022
United Nations Human Rights Office of the High Commissioner: *Countries & Territories Saudi Arabia*, 2022. URL: https://www.ohchr.org/en/countries/saudi-arabia#status-reporting--154 [Status: 15.07.2022].

Presseportal 2021
German LNG Terminal GmbH: *Technische Universität Hamburg untersucht Perspektiven geplanter Terminalinfrastruktur für eine zukünftige Energieversorgung im norddeutschen Raum*, 2021. URL: https://www.presseportal.de/pm/142930/5003119 [Status: 15.07.2022].

Prognos 2020
Kreidelmeyer, S./Dambeck,H./Kirchner, A./Wünsch, M.: *Kosten und Transformationspfade für strombasierte Energieträger,* 2020. URL: https://www.bmwk.de/Redaktion/DE/Downloads/Studien/transformationspfade-fuer-strombasierte-energietraeger.pdf?__blob=publicationFile [Status: 15.07.2022].

Prognos/ Öko-Institut/ Wuppertal-Institut 2021
Prognos/Öko-Institut/Wuppertal-Institut: *Klimaneutrales Deutschland 2045. Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann. Im Auftrag von Stiftung Klimaneutralität, Agora Energiewende und Agora Verkehrswende,* 2021. URL: https://www.agora-energiewende.de/veroeffentlichungen/klimaneutrales-deutschland-2045 [Status: 15.07.2022].

PtJ 2021
Projektträger Jülich: *Expertenempfehlung Forschungsnetzwerk Wasserstoff,* 2021. URL: https://www.forschungsnetzwerke-energie.de/lw_resource/datapool/systemfiles/agent/fnepublications/CB89EC28FD6325E2E0537E695E860C38/live/document/Expertenempfehlung_Forschungsnetzwerk_Wasserstoff.pdf [Status: 15.07.2022].

Schmidt et al. 2022:
Schmidt, M./ Stöcker, P. / Staiß, F. / Wurbs, S. / Stephanos, C.: *Optionen für den Import grünen Wasserstoffs nach Deutschland bis zum Jahr 2030 –* Materialband, 2022.

SPD, BÜNDNIS 90/ DIE GRÜNEN, FDP 2021
Sozialdemokratische Partei Deutschlands, Bündnis 90/Die Grünen, Freie Demokratische Partei: *Mehr Fortschritt wagen. Bündnis für Freiheit, Gerechtigkeit und Nachhaltigkeit. Koalitionsvertrag 2021— 2025 zwischen der Sozialdemokratischen Partei Deutschlands (SPD), Bündnis 90 / Die Grünen und den Freien Demokraten (FDP)*, 2021. URL: https://www.spd.de/koalitionsvertrag2021/ [Status: 15.07.2022].

Stiftung Umweltenergierecht 2021
Hoffmann, B./Halbig, A./Senders, J./Nysten, J.-V./Antoni, O./Müller, T.: *Auf dem Weg zum Wasserstoffwirtschaftsrecht?,* 2021. URL: https://energiesysteme-zukunft.de/fileadmin/user_upload/Veranstaltungen/Verschiedene/Stiftung_Umweltenergierecht_Wasserstoffwirtschaftsrecht.pdf [Status: 15.07.2022].

Transparency International Deutschland 2022
Transparency International Deutschland e.V.: *Korruptionswahrnehmungsindex 2021,* 2022. URL: https://www.transparency.de/cpi/ [Status: 15.07.2022].

TÜV SÜD 2021
TÜV SÜD Standard CMS: *Production of green hydrogen (GreenHydrogen)* 2021. URL: https://www.tuvsud.com/de-de/-/media/de/industry-service/pdf/broschueren-und-flyer/is/energie/tv-sd-standard-cms-70_grund--und-zusatzanforderungen-deutsch-englisch.pdf [Status: 09.08.2023].

VCI 2021
Verband der Chemischen Industrie e.V.: *2021 Chemiewirtschaft in Zahlen,* 2021. URL: https://www.vci.de/vci/downloads-vci/publikation/chiz-historisch/chemiewirtschaft-in-zahlen-2021.pdf [Status: 15.07.2022].

Viebahn 2019
Viebahn, P.: *Exploring the Potential Role of Carbon Capture and Storage (CCS) for Power Plants in the German and the International Context – a Multi-Dimensional Assessment Approach*, 2019. URL: https://repositorium.ub.uni-osnabrueck.de/handle/urn:nbn:de:gbv:700-202103114093 [Status: 15.07.2022].

Viebahn et al. 2019
Viebahn, P./Scholz, A./Zelt, O.: *Entwicklungsstand und Forschungsbedarf von Direct Air Capture – Ergebnis einer multidimensionalen Analyse*, Energiewirtschaftliche Tagesfragen 69. Jg./Heft 12, 2019. URL: https://epub.wupperinst.org/frontdoor/deliver/index/docId/7438/file/7438_Viebahn.pdf [Status: 15.07.2022].

World Bank 2022
World Bank: *World Integrated Trade Solution (WITS),* 2022. URL: https://wits.worldbank.org/Default.aspx?lang=en [Status 15.07.2022].

WV Stahl 2022
Wirtschaftsvereinigung Stahl: *Aktuelle politische Positionen zur Transformation der Stahlindustrie in Deutschland*, 2022. URL: https://www.stahl-online.de/wp-content/uploads/202202_PosPap_Aktuelle_politische_Positionen_Transformation.pdf [Status: 15.07.2022].

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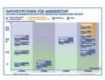
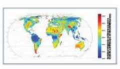
	Fig.1 | p.10	Energy Systems of the Future (ESYS); Illustration by Ellery Studio
	Fig.16 | p.77	Fasihi, M./Breyer, Ch.: Baseload electricity and hydrogen supply based on hybrid PV-wind power plants; Journal of Cleaner Production, Volume 243, 2020. URL: https://www.sciencedirect.com/science/article/pii/S0959652619333360?via%3Dihub [Status:: 15.07.2022].

The Academies' Project

In the Energy Systems of the Future initiative, acatech – National Academy of Science and Engineering, the German National Academy of Sciences Leopoldina and the Union of the German Academies of Sciences and Humanities provide input for a fact-based debate on the challenges and opportunities of the German energy transition. Around 160 experts collaborate in interdisciplinary working groups to develop policy options for the transition to a sustainable, secure and affordable energy supply.

Working group "Hydrogen Economy 2030"

Green hydrogen and synthetic energy carriers are key to the energy transition. But it can be safely assumed that Germany will not be able to meet its future demand through domestic production alone – not least because of the huge volumes of electricity produced from renewable sources that would require. This explains why imports have been garnering more and more attention as an option. That is the background behind the interdisciplinary working group that has been analysing the advantages and disadvantages of various transport options and assessing which of those options could be feasibly implemented by the year 2030. The working group has also been investigating the extent to which existing transport media and infrastructures could be used to import hydrogen into Germany and determining what would have to be created from scratch. The experts have also identified where the regulatory framework needs to be updated to lay the foundations for the hydrogen economy to be ramped up successfully by 2030.

The results of the working group's analysis are presented in two different formats:

1. The **analysis paper** "*Options for importing green hydrogen into Germany by 2030: transportation routes, country assessments and implementation requirements*" presents the results of the quantitative and qualitative analysis of the transport options conducted and introduces the methodology designed to assess countries, which has also been applied to some carefully selected countries by way of example.

2. The supplementary **material volume** guarantees transparency with its in-depth description of each stage of the generic analysis of the transport options and the the country assessments in the form of the exemplary transportation routes. Full details on all the sources referred to are also provided.

Working group members

Prof. Dr. Frithjof Staiß (Chair)	Center for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW)
Dr. Jörg Adolf	Shell Deutschland GmbH
Dr. Florian Ausfelder	DECHEMA Gesellschaft für Chemische Technik und Biotechnologie e.V. (Society for Chemical Engineering and Biotechnology)
Dr. Christoph Erdmann	MESSER GROUP GmbH
Prof. Dr.-Ing. Manfred Fischedick	Wuppertal Institute
Prof. Dr. Christopher Hebling	Fraunhofer Institute for Solar Energy Systems (ISE)
Dr. Thomas Jordan	Karlsruhe Institute of Technology (KIT) Institute for Thermal Energy Technology and Safety (ITES)
Prof. Dr. Gernot Klepper	Institute for the World Economy (IfW) Kiel
Dr. Thorsten Müller	Environmental Energy Law Foundation
Prof. Dr. Regina Palkovits	RWTH Aachen University – Institute for Technical and Macromolecular Chemistry
Dr. Witold-Roger Poganietz	Karlsruhe Institute of Technology (KIT)
Dr. Wolf-Peter Schill	German Institute for Economic Research (DIW Berlin)
Prof. Dr.-Ing. Ulrich Wagner	TUM (Technical University of Munich)
Dr. Kirsten Westphal	H2Global Foundation

Scientific coordination

Maike Schmidt	Center for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW)
Dr. Cyril Stephanos	ESYS Project Office | acatech
Philipp Stöcker	RWTH Aachen University – Institute for Power Electronics and Electrical Drives
Sven Wurbs	ESYS Project Office | acatech

Participating institutions

acatech – National Academy of Science and Engineering (lead institution)
German National Academy of Sciences Leopoldina
Union of the German Academies of Sciences and Humanities

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Oda Keppler (Guest)	Head of Directorate, Federal Ministry of Education and Research
Dr. Rodoula Tryfonidou (Guest)	Head of energy research unit, Federal Ministry for Economic Affairs and Energy

Project coordination

Dr. Cyril Stephanos	Head of Project Office "Energy Systems of the Future", acatech

Basic data

Project duration

03/2016 to 06/2024

Funding

The project is funded by the Federal Ministry of Education and Research (funding code 03EDZ2016).

SPONSORED BY THE

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Berlin Office:
Dr. Cyril Stephanos
Head of Project Office "Energy Systems of the Future"
Georgenstraße 25, 10117 Berlin
phone: +49 30 206 30 96 - 0
e-mail: stephanos@acatech.de

Series on "Energy Systems of the Future" (ESYS)

ISBN: 978-3-9820053-6-2