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Sino-German Energy Transition Project

The Role of Synthetic Energy Carriers in Sector Coupling

Perspectives for Germany and China

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

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The report "The Role of Synthetic Energy Carriers in Sector Coupling" is published by the German Energy Agency (dena) as part of the Sino-German Energy Transition Project. The project supports the exchange between Chinese government think tanks and German research institutions to strengthen the Sino-German scientific exchange on the energy transition and share German energy transition experiences with a Chinese audience. The project aims to promote a low-carbon-oriented energy policy and help to build a more effective, low-carbon energy system in China through international cooperation and mutually beneficial policy research and modelling. The project is supported by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) as part of the Sino-German Energy Partnership, the central platform for energy policy dialogue between Germany and China on a national level. On the Chinese side, the National Energy Administration (NEA) supports the overall steering. The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH leads the project implementation in cooperation with the German Energy Agency (dena) and Agora Energiewende.

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EWI-Study: The cost competitiveness of renewable hydrogen in China and Germany

1 Hydrogen Demand and Use

In addition to the first two principles of the energy transition, efficiency first and the direct use of renewable energy, hydrogen, being a storable, scalable and future cost-efficient molecule, can make a major contribution to achieving global net zero by coupling different application sectors.

By 2050, climate-neutral hydrogen could decrease CO_2 emissions by about 80 gigatonnes worldwide, representing 20% of the reductions required to limit global warming to 1.5 degrees. This potential will only be achieved if current hydrogen demand is replaced by renewable hydrogen demand and if new areas of application for renewable hydrogen are introduced. The total hydrogen demand is thus expected to increase in the coming years. [1]

To cover the current global demand of around 70 Mt of hydrogen, companies worldwide process about 205 billion m^3 of natural gas and 107 Mt of coal each year. This means that 76% of the hydrogen produced today is made from natural gas and 23% from coal. Electrolysis accounts for less than 2% of the total amount produced. The coal-based production pathway accounts for only about 2% of global coal consumption and is mainly concentrated in China. [2]

The refinery sector, ammonia and methanol production, and steel production are the main users of fossil hydrogen today. This shows the essential role of hydrogen as a base product for many different economic sectors, such as fuel for transport, fertilisers for agriculture and construction materials for the building sector. [2]

In Germany, about 40% of the hydrogen produced is used in refineries. 60% of the resulting products are fuel for the mobility sector. More than a quarter of the hydrogen is used as a component to produce ammonia, which is the main component of synthetic fertilisers. 20% of the hydrogen is used to produce methanol, which is needed, among other things, for the organic synthesis of plastics. The rest is distributed among various other industries in which hydrogen is used as a material component, such as metallurgy and glass production. [3]

The chemical industry often uses hydrogen indirectly as a synthesis product with carbon or nitrogen. The use and further processing methods are diverse: The most important chemicals for the industrial value chain are produced from synthesis gas, which in turn reacts in a mixture of hydrogen, carbon monoxide and carbon dioxide. In the production of diesel and petrol, on the other hand, hydrogen is used for the hydrodesulphurisation and hydrocracking of long-chain hydrocarbons.

Therefore, the main demand for hydrogen comes from chemicals such as ammonia and methanol, as well as from olefins: ethylene, propylene and aromatics such as benzene, toluene and xylene. In the ammonia and methanol production processes, hydrogen is used as a direct feedstock; for the production of olefins, there is not yet a process with a corresponding technology readiness level. However, intermediate products such as methane or methanol are required to produce olefins from hydrogen. [4]

Current pathways of hydrogen production via natural gas and coal gasification have a high decarbonisation potential to make the industrial processes, but also the products, more climate-friendly. One measure to reduce emissions is to capture the CO_2 emitted during hydrogen production and use it elsewhere or store it in the long term. The product of this fossil-based route with CCUS is often called blue hydrogen in Germany, and this is how it is referred to in this report. Conventional gas-based and coal-based processes result in grey hydrogen. To illustrate the German understanding of this colour theory, Table 1 shows the three most discussed production pathways in Germany.

Process	Colour Code	Feedstock	Energy Source
Conventional	grey	natural gas or coal	natural gas, coal
Conventional with CCS	blue	natural gas or coal	natural gas, coal
Electrolysis with renewable electricity	green	water	renewable energy

In addition to the fossil-based routes, hydrogen can be produced by splitting water into hydrogen and oxygen using electricity, a process known as electrolysis. The global warming potential of this electrolytic production route depends very much on the GHG emissions of the electricity used. However, if the electricity for electrolysis comes from renewable sources such as wind power or photovoltaics, GHG emissions can be reduced to (almost) zero. In Germany, this climate-neutral hydrogen is called green hydrogen. It should be emphasised that only electrolytic hydrogen produced from verifiably renewable electricity is considered green and not electrolytically produced hydrogen from grid electricity. German ambitions and targets, as well as most support programs, are very specific to green hydrogen.

In the global debate, reference is sometimes made to other colours, such as turquoise hydrogen, which refers to hydrogen production from natural gas via methane pyrolysis. These are not considered further in this report. Figure 1 compares the different GHG emission levels of the production pathways described. In addition to the significant emission reduction potential of green hydrogen compared to the conventional grey product, the wide range of the blue variants is particularly striking. The remaining GHG emissions for hydrogen production with CO_2 capture depend highly on the leakage rates in the upstream chain and the capture rates, which affect the price of the hydrogen. These assumptions and uncertainties reinforce Germany's decision to focus on green hydrogen.

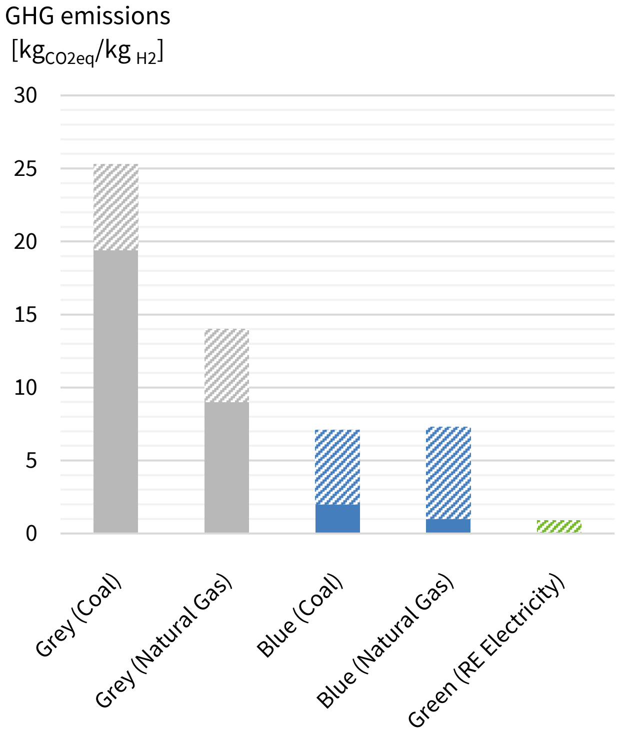

Figure 1 Greenhouse gas emissions of different hydrogen production pathways
The shaded area represents the range of emissions reported in different references or within one reference for different cases. The filled area represents the lower bounds of referenced findings (based on [2, 5, 6]).

Like the European Union, Germany has set ambitious climate targets. The German government aims to make all economic activities in the industrial and energy sectors, as well as in the transport and construction sectors, climate neutral by 2045. While the German power sector already obtains almost half of its energy from renewable sources, there is still much to be done in the other sectors. Since the production capacity of renewable feedstock such as synthetic gas is limited, coupling the different sectors is urgently needed. The German government is striving to electrify road transport, especially passenger transport, focusing primarily on battery electric vehicles. The heating sector for residential buildings and industrial applications can also be widely electrified. However, the current state of the art does not allow the electrification of other sectors, such as the chemical industry or special transport applications like maritime shipping and aviation.

In this respect, green hydrogen offers solutions that allow for a significant reduction in emissions without the need for fundamental changes in applications or processes.

The German Hydrogen Strategy published in June 2020 envisioned a domestic electrolyser capacity of 5 GW by 2030 and 10 GW by 2040. In the German government's coalition agreement of December 2021, this target was doubled to 10 GW of available electrolysis capacity by 2030. The expected demand ranges from 64 to 110 TWh in 2030 and from 392 to 657 TWh in 2045, as shown in Figure 2[1]. Only about 15% is expected to be covered by domestic capacity in 2030. Imports from Europe, but also from other countries, will be necessary. Figure 2 also shows a wide range in the composition of this demand. While some energy scenarios result in high demand for hydrogen itself, others foresee a much higher demand for its derivates, so-called Power-to-X products (abbreviated as PtX).

The EU's Hydrogen Strategy, adopted in July 2020, sets a target electrolysis capacity of 40 GW by 2030, and thus a production volume of up to 400 TWh of renewable hydrogen. Since hydrogen and PtX will continue to grow in importance as an intrinsic part of an integrated energy system, hydrogen production in 2050 might use about a quarter of renewable electricity in the EU.

The German Hydrogen Strategy does not explicitly restrict the use of hydrogen, but its first step focuses on an application in the chemical, steel, logistics and aviation industries, for example, through the development of decarbonisation strategies. However, the German government is also promoting the installation of fuel cell heating appliances in buildings, for instance. In the chemical sector, existing processes that currently use grey hydrogen, as described above, are to be converted to low-emission alternatives. Furthermore, Germany has set itself the goal of analysing where hydrogen is produced as a by-product, how it can be made usable and where excess production capacities may then arise.

[1] Figure 2 is based on [7].

China currently accounts for one-third of the world's hydrogen demand and, with 33 million tonnes of annual hydrogen production, is also the largest producer. As in Germany, hydrogen is used in the chemical industry, refineries and metallurgy.

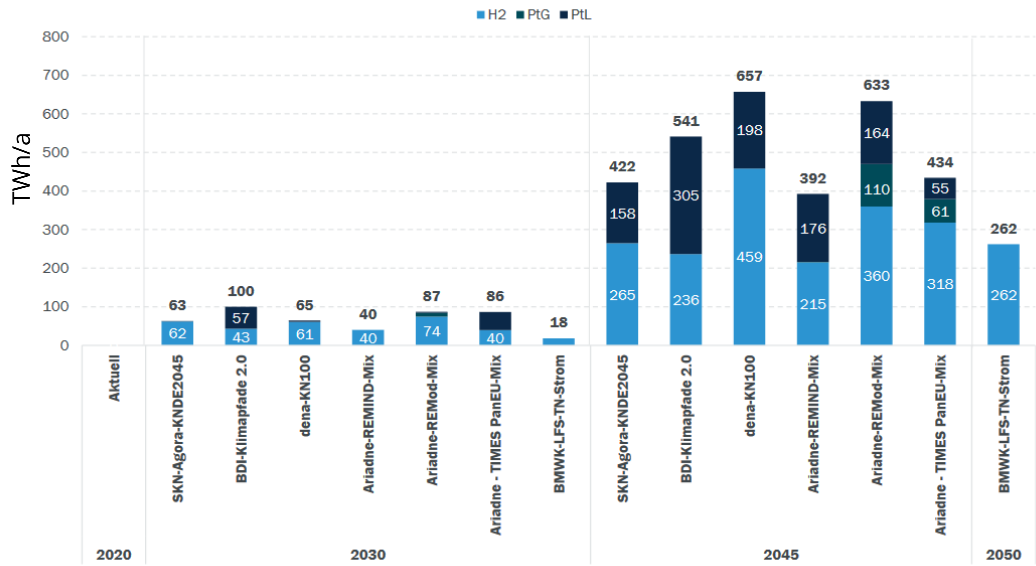

Figure 2 Demand for H2, PtG and PtL in comparison of the five major German energy system studies

In 2022, China published its long-term plan for the production and use of hydrogen. This national "Medium- and Long-Term Plan for the Development of the Hydrogen Energy Industry" for 2021 to 2035 sets a production target of 100,000 to 200,000 tonnes of green hydrogen for 2025. In principle, however, hydrogen use should be supported with a focus on the green product only set at a later stage. Therefore, it is difficult to compare the Chinese and German plans and ambitions due to the different definitions and underlying objectives that differ greatly. That is why this report focuses primarily on the development of sector coupling through synthetic energy carriers such as hydrogen in industry and specific areas of mobility.

In 2050, China's demand could then reach up to 100 million tonnes of renewable hydrogen. This means that 22% of global hydrogen demand in 2050 would be generated in China. In order to meet this high demand, China is currently expanding its electrolysis capacity. Current forecasts expect around 38 GW in 2030, with China's largest hydrogen lobby organisation (China Hydrogen Alliance) even publishing a plan for 100 GW in 2030 [8]. However, as in Germany, there are not enough plants in operation or planned to reach these targets [9].

The Mercator Institute for China Studies has identified four pillars on which China is focusing to support the market ramp-up:

1. R&D investments
2. Local and provincial policy support
3. Project development
4. Industrial build-up [9]

In addition to its use in the known application areas, hydrogen can take on many other tasks in the future energy system. Hydrogen makes renewable electricity storable over longer periods of time, transportable over longer distances and increases system resilience by coupling the electricity system with other parts of the energy system.

Due to their storage capability, hydrogen applications can also provide system services for the electricity grid. Peaks can be balanced out through intelligent control of electrolysers so that electricity grids are less strained, and the shutdown of renewable energy plants can be avoided. Furthermore, it is possible to convert the hydrogen back into electricity via fuel cells and thus balance out demand peaks. Thanks to its long-term storage capability, such as in old salt caverns, seasonal fluctuations in electricity supply and demand can also be balanced out. However, due to efficiency losses during conversion and reconversion, the costs and technical benefits of such applications must be carefully weighed.

The transportability of hydrogen and its derivatives in pipelines and via maritime shipping makes it possible to decouple locations with high potential for renewable electricity production and centres of demand for renewable energy sources. Renewable electricity products are thus tradable worldwide, and the use of otherwise unusable renewable potentials becomes economical. However, converting electrical energy into renewable molecules primarily enables the decarbonisation of many new applications, such as the use as a fuel in reaction with carbon atoms or as feedstock in combination with nitrogen for ammonia

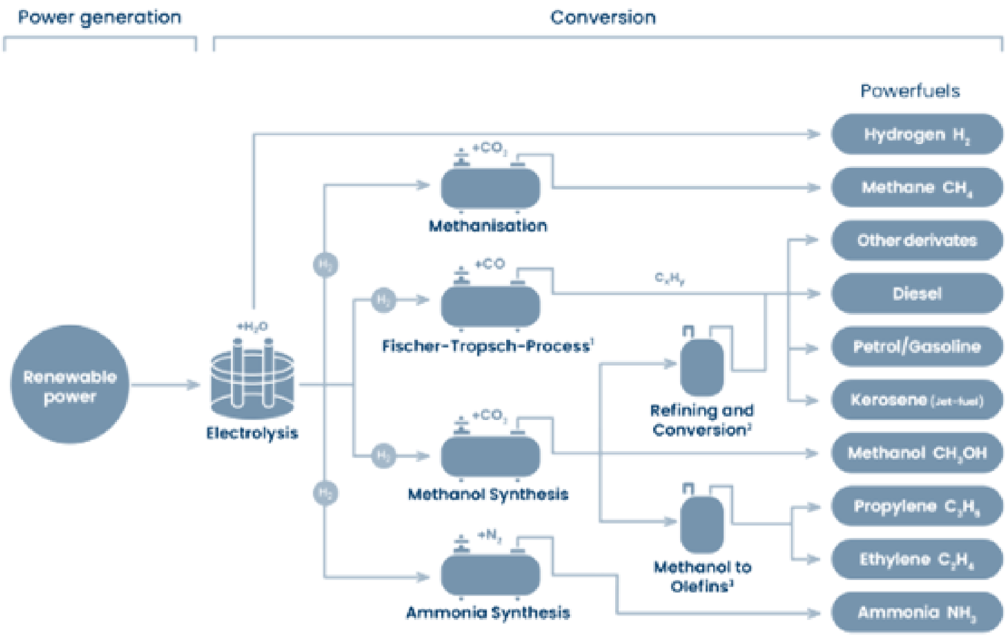

Figure 3 Various possible powerfuel processes, products and use cases [11]

synthesis or iron ore for direct reduction in steel production, for example.

To make the ramp-up of the hydrogen economy as efficient as possible worldwide, the significantly more expensive renewable hydrogen should, in future, be used primarily in those sectors that cannot be directly electrified. The public discussion between industry, science and other public stakeholders in the relevant sectors has been going on for several years. However, regardless of the research method and exact cost assumptions, four application areas are now recognised as secure sectors for hydrogen and PtX use: as a base material for the chemical, steel and iron industries, freight shipping and all air traffic.

In a comprehensive analysis, Ueckert et al. also identified high-temperature (> 400 °C) industrial process supply and heavy-duty road transport as energy-intensive sectors where e-fuels and direct electrification are likely to have similar costs [10]. The following section describes the four application areas that should start the transition to hydrogen or PtX deployment today without any remorse. The second part of this report then provides a detailed analysis of the competitiveness of green hydrogen as compared to its fossil equivalent. Use in shipping is excluded, as the technical developments are still ongoing in this area, and no variant shows a clear advantage to date.

1.1 Chemical industry

In the chemical industry, hydrogen is mainly used in the production of basic materials such as industrial gases or fertilisers, as well as the production of petrochemicals and derivatives. The decisive difference to the application in other areas is its use as raw material and not as an energy source.

Figure 3 [11] shows the various processes and products that can be produced from renewable hydrogen by conversion. For example, the Fischer-Tropsch process or methanol production and subsequent refining processes can be used to produce all the conventional fuels used in the transport sector today. Methanol is also a feedstock for thermosets, fibres, elastomers, solvents, additives and

INFOBOX

HySCALE100 is a large-scale hydrogen production and green methanol synthesis project to decarbonise the value chains of the two major industries of petrochemicals and cement. The project is led by Hynamics and partners Holcim Germany, Ørsted and Raffinerie Heide GmbH. (Schleswig-Holsteinischer Landtag 9/5/2022)

The project will be implemented with partners from the business community and the municipalities in the region to use regionally generated wind energy to produce green hydrogen. In this way, electricity can be stored and fed into the value chains of a wide range of industries. The goal is to produce green hydrogen on a large scale and use CO_2 to convert it into synthetic feedstocks. Along with cement produced sustainably in this way, a wide range of products is created, from e-fuels to e-chemicals and e-methanol. These measures will create the possibility in the West Coast region to absorb renewable energy and thus decarbonise the existing industries in the network. With the construction of the first electrolysis capacities of about 500 MW by 2025, hydrogen will be refined with CO_2 into methanol and then into synthetic chemicals. In a later stage, an output of 2125 MW is to be reached by 2027. (Orsted 9/5/2022)

The project can reduce Germany's total CO_2 emissions by 0.5% and will make a significant contribution to Germany's climate neutrality. Funding for HySCALE100 and 61 other projects throughout Germany is being provided as part of the IPCEI Hydrogen European funding initiative. (BMWI 9/5/2022) explosives. It should be noted that 25% of the world's methanol production alone is used in the manufacture of formaldehyde and, consequently, in the production of synthetic resins.

While petrochemicals and most basic chemicals are carbon-based, nitrogen is used to produce ammonia from hydrogen. As described above, ammonia is currently used primarily to manufacture fertilisers. However, it is currently being further developed into a zero-carbon fuel. For example, a joint report by IRENA and the Ammonia Energy Association discusses its use in stationary power generation and as a possible fuel for shipping. The potential of ammonia as a hydrogen carrier for international trade is also described in this report, as well as in other publications of recent years. Ammonia is already successfully shipped today, but the fleet would have to be expanded considerably. The advantage of not needing CO_2 for production is partly offset by the high toxicity and the risk to aquatic environments. [12] Germany is already planning the first ammonia import terminal in Brunsbüttel. The energy company RWE would like to unload up to 300,000 tonnes of green ammonia per year for the future production of nitrogen fertilisers and mineral oil products in the port on the River Elbe [13].

1.2 Steel industry

Germany's 20 steel plants produced 42.4 million tonnes of crude steel in 2018, 70% of which was produced via blast furnace and converter and 30% by electric arc furnace. This led to 57.8 million t of direct CO_2 emissions in 2018, including the further processing of the crude steel. There are three different ways to unlock this large potential to reduce emissions:

1. Replace fossil fuels such as co-gas and natural gas with hydrogen in the further processing of the crude steel
2. Increase the percentage of steel produced by electric arc furnace using green electricity and, in the long term, using climate-neutral hydrogen in natural gas burners at the electric arc furnace
3. Shift to primary steel production by means of direct reduction with green hydrogen and transitional hydrogen-rich gases such as natural gas in combination with the use of CCS/CCU. Complete conversion to green hydrogen increases the CO_2 avoidance potential of this shift up to 95% compared to the blast furnace route.

Hydrogen demand in the steel industry could thus increase to 45 TWh in 2030 and 123 TWh in 2050 in Europe alone [14].

To enable the steel industry to invest in low-CO_2 steel production and create planning security, concrete prospects for creating substantial sales markets are needed. Standards and product labels are important prerequisites for developing sales markets for green steel. [15, 16]

INFOBOX

Steel producer ArcelorMittal is planning to convert many of its steel production facilities to a green hydrogen plant. The main objective is the conversion and operation of the existing DRI plants, which are currently operated with natural gas, to partial operation with green hydrogen.

ArcelorMittal Hamburg GmbH is the only steel plant in Western Europe to operate a direct reduction plant in which iron ore pellets are converted into metallic iron using a reduction gas instead of coke. According to the company, the reduction gas already consists of around 60% hydrogen, so the shift to full hydrogen is obvious. It is planned that 100,000 tonnes of hydrogen-based steel will be produced as early as 2025. By 2030, ArcelorMittal plans to produce more than one million tonnes of carbon-neutral steel per year, saving around 800,000 tonnes of CO_2 emissions annually. [13]

The conversion will involve considerable financial investment. The German government has expressed its intention to support the construction of the plant with 55 million euros, which corresponds to half of the required total investment of 110 million euros. The next step is for the European Commission to approve the German government's intention to provide funding before construction of the new plant can begin. ArcelorMittal has applied for funding under the European Union's IPCEI framework for its Hamburg plant.

In future, the ArcelorMittal site in Duisburg will be able to use green sponge iron (DRI) from Hamburg to produce steel as part of the DRUIDE project in Duisburg. At its Bremen site, ArcelorMittal plans to reduce CO_2 emissions first by supplying the blast furnace with natural gas and then with hydrogen. An electrolyser shall contribute to the production of climate-neutral hydrogen with an initial capacity of 100 MW to be increased to 300 MW. At their Eisenhüttenstadt site, the use of hydrogen is an integral component of the future strategy. In the long term, the aim is to change the technology to direct reduction of iron ore with hydrogen; however, in a transition phase, natural gas will initially be injected into the blast furnace until green hydrogen is available in the required volume and at competitive costs. [14]

As the largest producer and, at the same time, consumer of steel, this sector has a very high potential on the path to climate neutrality for China. Therefore, many pilot projects are already being set up for the various emission reduction variants, and some are already operational. The use of hydrogen in the DRI route is politically supported. In the RMI's zero-carbon scenario, primary steel would represent the second largest share after secondary steel via the renewable DRI route. To achieve this, the price of hydrogen would have to fall sharply, and the price of coal would have to rise. [17]

1.3 Aviation

The aviation industry is also currently facing the challenge of finding a way to transition towards low-emission air transport. According to the EU Green Deal 2050, transport-related emissions in the EU are to be reduced by 90% compared to 1990. Aviation accounts for 3.8% of total emissions in the EU and is the second largest emitter of GHGs in the transport sector after road transport, accounting for 13.9% of transport-related emissions. [18]

Thanks to efficiency improvements, the increase in CO_2 emissions can be decoupled from transport growth. However, emissions will continue to increase in the long term due to the current demand for air transport services.

Technically alternative propulsion technologies can be based on battery electric and fuel cell electric architectures. Both technologies are still at the research stage and partly at the testing stage [19]. For example, Airbus has announced that it will launch long-range hydrogen aircraft in 2035 [20]. By contrast, the CEO of aircraft manufacturer Boeing announced in June 2021 that he did not see a significant role for hydrogen in aviation before 2050 [21].

Overall, the direct use of hydrogen as an end-use energy carrier in commercial aviation remains highly uncertain. A possible scenario for its use was published by the industry-driven initiative "Destination 2050" at the beginning of 2021. In this scenario where European aviation achieves net-zero emissions in 2050, hydrogen accounts for up to 20% of the reduced emissions in 2050 [22]. Battery electric aircraft offer another alternative. Due to the limited energy density of batteries and their expected development, battery electric aircraft are not expected to play a role before 2030 ([23], [19]). From 2030 onwards, they could possibly be used for short-haul flights for 100 passengers [24].

Due to the high investment costs and the long life of aircraft, aviation needs a solution that also takes into account the reduction of carbon emissions for the current fleet generation. The high energy demand combined with safety parameters leads to stringent requirements for aviation fuels, such as high volumetric and gravimetric energy density and specific handling properties. Synthetic paraffin can be chemically identical to its respective fossil counterpart and meets all performance and safety specifications. E-kerosene can be blended with conventional kerosene as a drop-in fuel, or it can even replace it completely. It is therefore expected that by 2050 most demand will be met by aviation kerosene.

Two fuels of interest to civil aviation are thus hydrogen and e-kerosene. E-kerosene is a ready-to-use fuel that, when produced with green hydrogen and CO_2 from direct air capture (DAC), produces up to 90% less greenhouse gas emissions over its life cycle than fossil Jet A/A-1 [11]. The use of e-kerosene can further contribute to the mitigation of non-CO_2 effects, as it does not contain sulphur, unlike fossil jet fuel, and its combustion produces lower NOx emissions than fossil jet fuel [25]. However, it should be noted that when non-CO_2 effects are taken into account, the reduction in fuel warming effects that can be achieved by using e-kerosene compared to fossil jet A/A-1 is about 50% [18].

If green hydrogen is used directly as the final energy carrier, CO_2 emissions from fuel combustion are reduced by 100%. Even if non-CO_2 effects are taken into account, green hydrogen can still significantly outperform e-kerosene. If green hydrogen is used in combustion, the heating effect of the fuel can be reduced by 50%–75%. If green hydrogen is used in fuel cells, the reduction can be up to 90% [26].

Another factor to consider in the use of aviation fuels is their current price, which is significantly higher than conventional Jet A/A-1. To some extent, this may be industry specific, as aviation faces a rather high elasticity

INFOBOX

In October 2021, the world's first plant for the production of CO_2-neutral synthetic kerosene was inaugurated in Emsland in northwest Germany.

In a first step, an electrolysis plant produces hydrogen from renewable electricity and water. A synthesis unit then combines hydrogen and carbon. Since the CO_2 is extracted from the waste gas of a local biogas plant and via direct air capture, a closed carbon cycle is created, making the e-kerosene CO_2 neutral.

According to the operator, atmosfair, the plant has been operating regularly since this year and produces eight barrels of raw paraffin every day. Trucks take it to the refinery in Heide, north of Hamburg, where the synthetic crude oil is refined into finished Jet A1 aircraft fuel before it is delivered to Hamburg Airport. The Lufthansa Group, which is the largest buyer of sustainable aviation fuels (SAF) in Europe, is the first pilot customer for this project.

The production costs are still above 5 euros per litre, but atmosfair sells the product to its customers at a cost-covering price [24].

of demand, especially when such price increases are not global.

reflect the urgency of climate change action while remaining accessible to stakeholders.

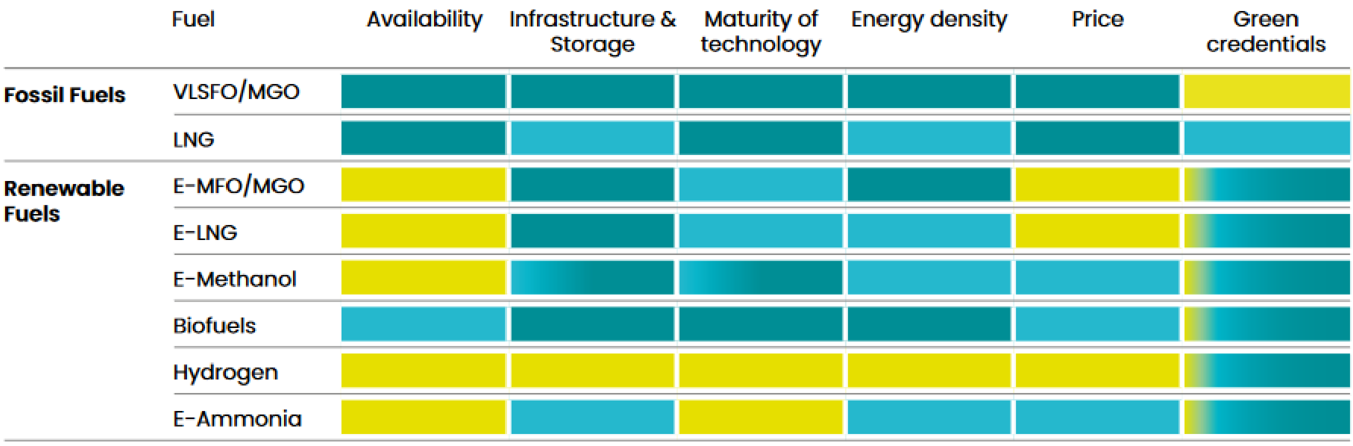

Figure 4 Characteristics of alternative shipping fuels

1.4 Maritime freight shipping

Greenhouse gas emissions from shipping accounted for about 2.89% of total emissions in 2018. In addition, the sector consumes about 8% of the world's annual oil supply. Between 2012 and 2018, GHG emissions increased from 977 million tonnes to 1,056 million tonnes, although the carbon intensity of shipping has improved significantly since 2008. Maritime transport is the backbone of global trade and accounts for more than 80% of global freight. [28]

Today, the world's maritime shipping fleet mainly uses low-sulphur fuel oil and gas oil to operate ships, which are burned as fuel in mono-fuel diesel engines. Most new ship orders continue to use this technology. The only alternative fuel currently available for commercial use is fossil LNG, which could reduce CO_2 emissions by up to 25%. However, fossil LNG is only considered a transitional fuel due to its very limited potential to reduce greenhouse gas emissions and the high risk of methane slip. [29]
A complete transition to other fuels is needed for shipping to move away from fossil fuels. This is a challenge for shipping companies, ports, fuel suppliers and policymakers. At present, there is great uncertainty about what the fuel mix in shipping will look like in the future. However, it seems certain that renewable electricity-based fuels will play an important role and complement biofuels.

In its 2019 Greenhouse Gas Strategy, the International Maritime Organisation (IMO) set a 50% emission reduction target for shipping by 2050 compared to 2008 [30]. In 2021, the European Commission adopted the "Fit for 55" package, which aims to adapt the EU regulatory framework to the increased climate target of a 55% reduction in emissions by 2030 and includes specific targets for maritime transport. Ambitious greenhouse gas emission reduction targets must be high enough to

With the revised Renewable Energy Directive, the EU has introduced an obligation to bring new fuels to market. In this context, consistency with the objectives of the FuelEU Maritime Regulation is important to ensure demand for the fuels available on the market. In the Renewable Energy Directive II (REDII) and its delegated acts, the EU defines the methodology for assessing the GHG emission reductions achieved by alternative fuels and sets sustainability criteria. The impact of different fuels on GHG emissions must be transparent to ensure that a real GHG reduction is achieved. The criteria for renewable fuels of non-biological origin and the methodology for calculating emission factors are currently under discussion in the REDIII negotiations.

In addition to the FuelEU Maritime regulation, the EU is committed to promoting comprehensive measures to develop a similar framework at the international level. This is reflected in the EU's proposal for an IMO standard for low greenhouse gas emitting fuels and LCA guidelines for fuels. The ultimate goal is a global fuel standard for greenhouse gases. If an international greenhouse gas standard for fuels is adopted and implemented globally, the EU framework will take a back seat, and global action could be prioritised.

Energetic fuels are considered the most viable option for decarbonising shipping in this century. As shown in Figure 4, current dual-fuel marine engines can use synthetic methane or liquid FT (Fischer-Tropsch) as alternative fuels, and there are already engines on the market that run on methanol. New engines are currently being developed to use ammonia as a fuel. In addition, fuel cells offer the possibility of using hydrogen directly. However, energetic fuels are not yet commercially available and competitive with fossil fuels.

It is difficult to identify clear winners among the various alternative fuels. Factors to consider include availability, infrastructure and storage, technological maturity (fuel and drivetrain), energy density, price and environmental friendliness of the fuels. Since ships are typically in service for two to three decades and retrofitting onboard fuel systems is very costly, there is a lot of uncertainty about the future of maritime fuels. This uncertainty inhibits investment, as there is a risk of stranded assets. [31]

2 Hydrogen Economics

The costs of green hydrogen are currently still significantly higher than those of the fossil equivalent. The competitiveness of renewable hydrogen depends on supply costs and end users' level of willingness to pay. Provision costs consist of production costs and transport costs. Production costs for renewable hydrogen are mainly composed of electricity costs, other OPEX and the CAPEX of the electrolysis plant [32]. Transport costs depend on the transport mode, i.e. pipeline, ship, truck, etc. and can vary greatly depending on the distance between the production and consumption site.

Stimulating a shift to zero-emission and low-emission variants can be done either by supporting renewable hydrogen and thus reducing supply costs or by making the fossil product more expensive to use, thus increasing users' willingness to pay. Supporting the reduction in the cost of renewable hydrogen entails subsidising the various cost components, such as the electrolyser or the electricity, but also incentivising its use, for example, through mandatory use quotas. On the other hand, carbon pricing increases the cost of using fossil products with high GHG emissions and makes the renewable option increasingly attractive. [33]

These measures can be further divided into three categories: those that cost the state money by paying a premium or subsidy; those that earn the state money, such as penalties; and those that neither cost nor make money, such as quotas. A broad funding landscape always carries the risk of using too much public money and thus unnecessarily intervening in processes that the market would produce in any event or delaying technical or economic developments, such as the prioritisation of application sectors. Therefore, it is urgently necessary to continuously evaluate the efficiency and effectiveness of the policy measures and make adjustments where necessary.

The Hydrogen Council published a Policy Toolbox in 2021 that identifies six pillars for effective policy:

1. Make use of local strengths & benefit from cross-border cooperation
2. Create certainty through targets and commitment
3. Provide hydrogen-specific support across the value chain
4. Support robust carbon pricing
5. Adopt harmonised certification schemes
6. Factor in societal value and values [34]

Germany has already been able to introduce many measures for pillars 1 and 2 with the publication of its own hydrogen strategy and the various processes at the EU level. In addition, the European Union is currently revising and expanding its regulatory framework, e.g. the maritime sector was added to the Emissions Trading Scheme (pillar 4), and a methodology for the certification of low-carbon and renewable hydrogen is also being developed (pillar 5). Moreover, a variety of measures and support instruments are already in use in Germany. These range from the promotion of scientific contributions and technical development and testing to direct subsidies for the construction or conversion of industrial plants using hydrogen to measures to support the international market ramp-up and enable the import of hydrogen and its derivatives (pillar 3).

In contrast to Germany, China relies less on diverse national targets for application areas and sectors but rather on specific measures at the provincial level. Therefore, it relies primarily on pillar 1 and the use of respective local strengths. For example, in 2021, 78 policies were adopted at the provincial level that mention hydrogen or fuel cells, while at the national level, these terms were used in only 11. Nevertheless, China has set strict and ambitious targets for achieving carbon neutrality, and renewable hydrogen is an important building block on this path. The introduction of a carbon pricing mechanism (pillar 4), for example, makes the shift to green hydrogen increasingly attractive. In addition, there is the desire to become less dependent on fossil imports, especially natural gas imports, which could also be achieved by developing renewable hydrogen production.

2.1 Results

As described above, hydrogen-specific support is partly already being implemented while also partly still in the design phase. In the second part of this report, the Institute of Energy Economics at the University of Cologne (ewi) conducted a quantitative study of the cost competitiveness of renewable hydrogen in China and Germany. In each case, the levelised cost of hydrogen from electrolysis was compared with the currently used fossil alternatives for the three "no-regret" application sectors of the chemical industry, the steel industry and aviation.

The results show that support measures are necessary in all three application examples to ensure that the shift to the electricity-based variant of hydrogen takes place as quickly as possible. However, the results also show that the cost gap is significantly larger in aviation than in the two heavy industries.

The second part of the report also evaluates five different support measures for their impact on the competitiveness of renewable hydrogen. The evaluators conclude that a combination of carbon pricing and sector-specific OPEX and/or CAPEX subsidies will have the greatest positive impact on market uptake. The results also show that especially the direct OPEX and CAPEX subsidies for e-kerosene must be very high to achieve cost parity with fossil paraffin.

2.2 Conclusion

Overall, the quantitative results lead to the conclusion that a robust carbon pricing mechanism in the chemical and steel sectors would close the cost gap between fossil and conventional methods and those using synthetic energy sources via the green production route in 2030 in Germany and 2035 in China. Carbon prices of around $80/tCO_2$ in Germany and less than $20/tCO_2$ in China are sufficient for this. The sooner the carbon price takes effect in these sectors and is sufficiently high, the sooner the shift to the low-emission option is likely to occur, at best, even without further government intervention.

In the aviation sector, the situation is clearly different. Carbon pricing would have to reach several hundred US dollars to close the cost gap. Not only is this unlikely, but it would also place a heavy burden on consumers. Even a full subsidy of the investment costs of the electrolyser is not enough to reach the price levels of fossil kerosene, neither in Germany nor in China. In order to nevertheless reduce emissions, an ambitious e-kerosene quota is the most effective and inevitable method. The restrictive nature of such a quota can also stimulate the technical development of other technology variants without increasing costs for the public. Furthermore, higher consumer prices may lead to a modal shift to other modes of transport, decreasing the total number of flights and, thus, the total GHG emissions.

In conclusion, Figure 5 presents three suggestions for measures that can be taken to accelerate the shift to renewable energy carriers (see below).

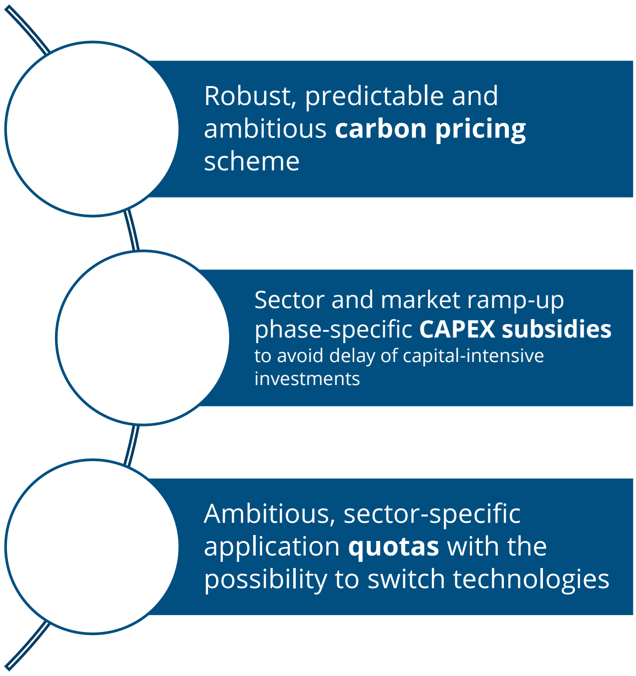

Figure 5 Summary of the most important measures to accelerate the use of synthetic energy sources in sector coupling

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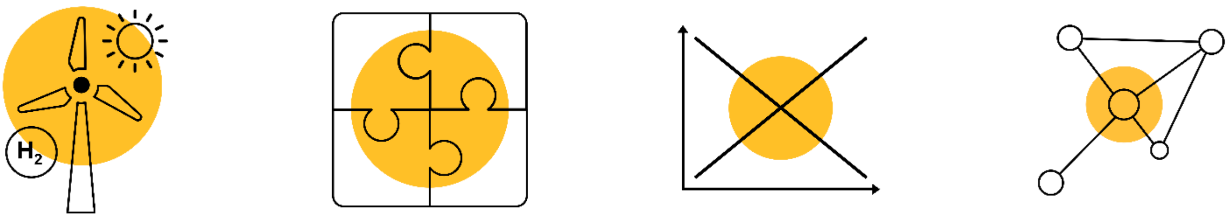
[EWI-Study]

The cost competitiveness of renewable hydrogen in China and Germany

An analysis of the chemical, steel and aviation sector

On behalf of Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

April 2022



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The Institute of Energy Economics at the University of Cologne is a non-profit limited liability company (gGmbH) dedicated to applied research in energy economics and carrying out projects for business, politics, and society. Annette Becker and Prof. Dr. Marc Oliver Bettzüge form the institute management and lead a team of more than 40 employees. The EWI is a research facility of the Cologne University Foundation. In addition to the income from research projects, analyzes, and reports for public and private clients, the scientific operation is financed by institutional funding from the Ministry of Economics, Innovation, Digitization and Energy of the State of North Rhine-Westphalia (MWIDE). Liability for consequential damage, in particular for lost profit or compensation for damage to third parties, is excluded.

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1 Drivers of hydrogen costs and competitiveness of renewable hydrogen

A rapid ramp-up of hydrogen technologies is essential for China and Germany to decarbonise their industrial and transport sectors. This chapter investigates the competitiveness of renewable hydrogen and the suitability of various policy instruments to make a hydrogen ramp-up as economically efficient as possible. The competitiveness of renewable energy sources (RES)-based hydrogen in different end-use applications depends on the cost gap between the RES-based hydrogen technology and the conventional emission-intensive technology. In the following, the competitiveness of renewable hydrogen in different applications in the chemical industry, aviation, and the steel industry will be evaluated and the effects of selected policy instruments will be illustrated for China and Germany.

1.1 Methodology

We create techno-economical process models to estimate and project levelized production costs for hydrogen, hydrogen-based synthetic kerosene, and steel for Germany in 2030 and China in 2035. First, we assess hydrogen production for the chemical industry, where RES-based hydrogen can substitute conventional hydrogen from natural gas reforming or coal gasification. Essential cost drivers in this sector are the cost of conventional hydrogen determined by natural gas and lignite prices, (potential) additional cost of purification and the CO_2 price. Secondly, we analyze the steel industry. We compare the costs of direct reduced iron (DRI) plants using RES-based hydrogen with other steel plants using fossil feedstocks. Thirdly, we consider e-kerosene production for aviation, a synthetic fuel produced from RES-based hydrogen, electricity and CO_2. The competitiveness depends on the cost gap between e-kerosene and fossil kerosene.

The following is a general description of the methodology. All production plants presented below are assumed to be fully integrated, i.e. hydrogen production and subsequent process steps are assumed to be in close proximity to one another. The sizing of the individual components is designed for minimum production cost. All plants are energetically integrated with closed energy balances. Mass balances are simplified. Electrolyzers and direct air capture (DAC) plants operate scheduled to optimize their capacity factors and minimize their hydrogen production costs. Electrolyzers can draw power from the power grid or directly from RES by power purchase agreements (PPAs).

In the case of PPAs, we use capacity factors for electrolyzers and electricity costs from (Moritz et al. 2021). The electricity costs from PPAs include capital costs of the generation units. All assumptions on grid electricity are adopted from the section (dena and EWI 2022: Sino-German Energy Transition Project (EnTrans) - Energy efficiency & Demand Side Management). For grid electricity, we optimize the capacity factors of the electrolyzers to attain minimal levelized costs of hydrogen. We determine the individual electricity price and carbon footprint of electricity for scheduled units.

DAC in kerosene production is scheduled identically to the electrolyzer. We assume all other process units to operate at steady state. The necessary hydrogen storage for integrated plants is estimated based on optimization results from (Moritz et al. 2021). An air separation unit supplies oxygen for coal gasification and steelmaking. In case of steelmaking, plants with electrolysers utilize the oxygen byproduct from the electrolyser.

In the case of CCS, we distinguish different carbon capture plants; their operational expenditures (OPEX) and capital expenditures (CAPEX) are based on (Hasan et al. 2014). Moreover, we include costs for dehydration of the gas stream (Hasan et al. 2012), compression of the CO_2 stream, CO_2 transport and storage (Smith et al. 2021).

In steelmaking, we only consider the system up to the furnace exit. The product is liquid steel. For all sectors, we consider process emissions on the scope-2 level which includes direct process emissions as well as indirect emissions from purchased power or heat.

Parameter		Germany	China	Source
Base year	-	2030	2035	
Depreciation period	a	20	20	(Green and Perry 2007)
Weighted average cost of capital (WACC)	%	4.88	6.92	(Moritz et al. 2021)
Hourly wage rate	$/h	48	16	(Schröder 2019)
Lignite	$/t	20.6	20.6	(International Energy Agency 2019)
Thermal coal	$/t	66	74	(International Energy Agency 2021), Announced Pledges Scenario
Natural gas	$/MWh	22.2	28.7	(International Energy Agency 2021), Announced Pledges Scenario
Iron ore (pellets)	$/t	120	120	(Germeshuizen and Blom 2013); (steelonthenet 2022)
Flux (mix of limestone and dolomite)	$/t	150	150	(Roberts 2009)
Water	$/t	2	2	(Moritz et al. 2019)
Electricity costs PPA	$/MWh	39	23	(Moritz et al. 2021)

Table 1: Key assumptions

From an economic perspective, all plants are assumed to be price takers. Due to the scheduling described above, process units can be oversized. Moreover, typical plant sizes, e.g., steel plants, differ between Germany and China. We consider the economy of scale for process equipment and account for the share of labour costs in fixed capital investments. As interest rates affect capital costs, we consider country-specific differences in the weighted average cost of capital (WACC). Fixed operational costs consist of labour costs and maintenance costs. To estimate labour intensity, we consider the number of individual process steps of the integrated plants (Green and Perry 2007). Labour costs comprise working labour, supervision and miscellaneous labour costs. We consider differences in typical wages for industrial works between Germany and China and account for the share of labour costs in fixed capital investments. Variable operational costs are costs for feedstock and energy. Table 1 gives an overview of key economic assumptions. Moreover, we assume that coal gasification is unavailable in Germany due to its policy to phase out coal-fired power. Also, CCS is not considered an option in Germany due to three reasons. Firstly, studies project that Germany can reach climate neutrality without domestic CCS (Energiewirtschaftliches Institut an der Universität zu Köln 2021; Umweltbundesamt 2019), secondly, there are widespread political and public concerns against CCS (Schleswig-Holsteinischer Landtag 9/26/2019) and thirdly, German law has high requirements for the implementation of a storage project in Germany (Umweltbundesamt 1/15/2021).

1.2 Hydrogen

Hydrogen is an important basic material for the chemical industry such as the ammonia industry or the petro-chemical industry. The projected levelized cost of hydrogen production from different production pathways for Germany in 2030 and China in 2035 are presented in Figure 1.

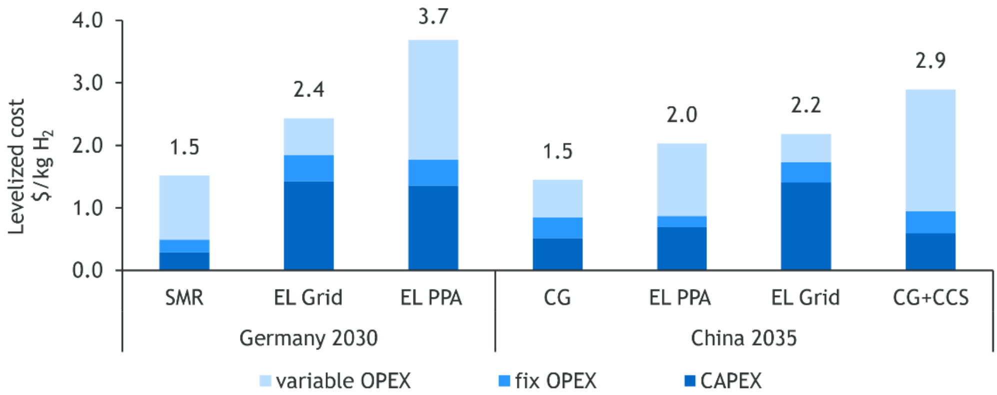

Figure 1: Levelized cost of hydrogen production. Abbreviations: EL Grid - Electrolysis from grid electricity, EL PPA - Electrolysis from PPA of designated renewables, SMR - steam methane reforming, CG - Coal gasification, CG+CCS - Coal gasification with carbon capture and storage.

For Germany, steam methane reforming of natural gas (SMR) is projected to be the lowest-cost option in 2030. With levelized hydrogen production costs of \$1.5/kgH_2, SMR, currently the conventional technology used to produce hydrogen in Germany, comes out ahead of electrolysis using grid electricity (\$2.4/kgH_2). The levelized cost of hydrogen produced by SMR is dominated by the variable OPEX, mainly the cost of natural gas. Electrolysis using grid electricity outperforms electrolysis using electricity sourced from dedicated RES through PPAs from photovoltaic powerplants (\$3.7/kgH_2). The cost of grid-based electrolysis presented here is contingent on 730 hours per year with electricity prices close to, at or even below zero. A greater proliferation of storage and increasing competition for low-cost electricity from additional electrolysers and rival consumers, such as heat pumps or electric vehicles, could lead to an increase in power prices in these critical hours, eroding the competitive advantage of grid-based electrolysis over electrolysis powered by dedicated RES.

In China, coal gasification is the least costly but the most emission-intensive hydrogen production pathway ($1.5/kg$H_2$). Coal gasification involves processing solid lignite, which is more capital intensive than a gas processing plant such as steam methane reforming. However, the variable OPEX of coal gasification are smaller than of SMR due to the price difference between lignite and natural gas. The CCS technology can be applied to capture and store most of the associated emissions from coal gasification and SMR. CCS, however, reduces the efficiency of the production process and requires significant additional electricity, increasing the levelized cost of hydrogen produced from coal gasification with CCS to $2.9/kg$H_2$. This puts coal gasification with CCS behind electrolysis. Hydrogen from electrolysis is projected to yield production costs of between $2.2/kg$H_2$ and $2/kg$H_2$ by 2035, depending on the source of electricity (the power grid or stand-alone RES/PPAs). In contrast to Germany, in China electrolysis using PPAs competes against grid electrolysis for two reasons. Firstly, in the scenario at hand China has RES with higher capacity factors than Germany. Secondly, the Chinese power system in 2035 has less than 700 hours per year with electricity prices at or near zero (dena and EWI 2022: Sino-German Energy Transition Project (EnTrans) - Energy efficiency & Demand Side Management).

1.3 Steel industry

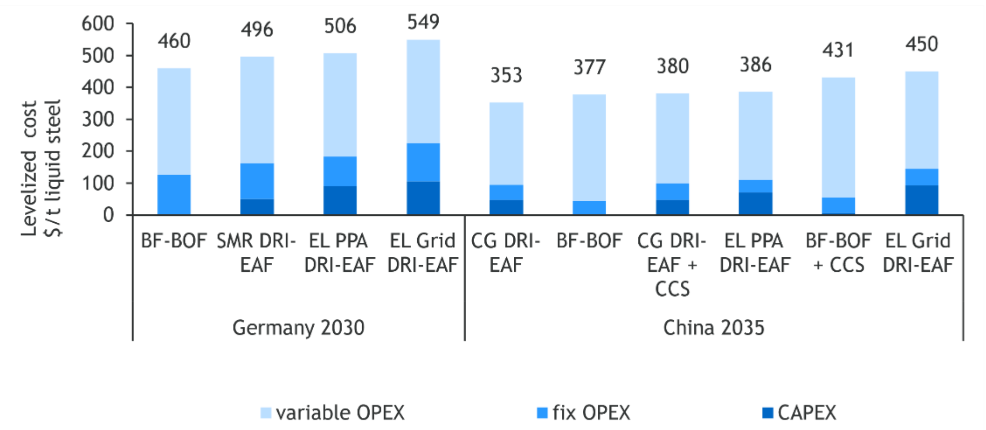

Figure 2: Levelized cost of steel production. Abbreviations: EL Grid DRI-EAF - DRI-EAF using electrolytic hydrogen from grid electricity, SMR DRI-EAF - DRI-EAF using syngas from steam methane reforming, EL PPA DRI-EAF - DRI-EAF using electrolytic hydrogen from PPA of designated renewables, CG DRI-EAF - DRI-EAF using syngas from coal gasification, CG DRI-EAF + CCS - DRI-EAF using syngas from coal gasification with carbon capture and storage, BF-BOF+CCS - BF-BOF with carbon capture and storage.

The steel industry is a major emitter of GHG emissions due to its energy intensity and emissions linked to the reduction of iron ore. In the following section, the cost analysis for steelmaking is discussed. We distinguish the process routes between the steelmaking process type and the reducing agent. We consider the blast furnace (BF) as conventional technology where iron ore is reduced to pig iron using coke and subsequently refined to steel in a blast oxygen furnace (BOF). In 2020, the BF-BOF process had a share of 68% in the German and 90% in the Chinese steel produced (World Steel Association 2019). The process is emission-intensive as the heat demand is covered by coal, and reducing iron ore with coke produces CO_2 inherently. As an alternative technology, we consider the direct reduction iron process (DRI) which uses syngas to reduce iron ore to iron sponge which is subsequently refined to steel in an electric arc furnace (EAF). The DRI-EAF technology emerged in the 1980s and is considered state of the art today. The EAF is well established in Germany to produce secondary steel from scrap. However, within this evaluation, we focus on primary steel.

In comparison to the BF-BOF, the DRI-EAF is substantially less emission-intensive. The emission intensity of the process is highly sensitive to the reducing agent used in the DRI and the carbon footprint of electricity used for the EAF. Utilizing hydrogen as a reducing agent in the DRI avoids inherent CO_2 emissions entirely. Hence, the DRI-EAF process can be climate-neutral if renewable hydrogen and renewable electricity is used. Today, the DRI with hydrogen is in its pilot phase in Germany and China (Chen et al. 2021). Plant operators conclude that there are no technological barriers to using only hydrogen as a reduction agent in the DRI (ArcelorMittal Deutschland 2022). Thus, we assume this process to be available in 2030. For the BF-BOF processes, we exclude capital costs since significant capacities exist in Germany and China. We consider greenfield investments for all other steel plants (including CAPEX of CCS in case of the BF-BOF+CCS).

Figure 2 displays the cost analysis for steelmaking. In general, electrolysis-based processes are the least labour-intensive processes, followed by coal gasification or SMR DRI-EAF. Variable OPEX are dominated by iron ore costs, which make up about 60% of the variable OPEX. The BF-BOF is the most competitive technology in Germany, followed by the SMR DRI-EAF. The hydrogen DRI-EAF with PPA and using grid electrolysis are considerably more costly. In China, the DRI-EAF with coal gasification is the most competitive technology. It is followed in a close cost range by the BF-BOF, the DRI-EAF with coal gasification and CCS and the DRI-EAF with PPA. Compared to Germany, in China, the BF-BOF is not the most economical process despite having no CAPEX. This is firstly due to lower capital costs in China caused by low labor costs and secondly due to higher capacity factors of Chinese steel mills which reduces the share of capital costs in the levelized production costs. Electrolysis with PPA is more economical in China than grid electrolysis. This is mainly due to the reasons previously discussed in section 1.2.

1.4 Aviation

E-kerosene is necessary for the aviation sector's decarbonization as direct electrification of aviation is technically challenging. E-kerosene can be produced by Fischer-Tropsch (FT) synthesis. The FT synthesis converts a feed of hydrogen and carbon dioxide to several coupling products such as synthetic gasoline, kerosene or diesel. If the hydrogen is RES-based and the CO_2 is drawn from the ambient air via DAC, we consider the produced kerosene RES-based. We consider a process variant designed to run with grid electricity and a variant designed to operate with electricity from PPAs.

Figure 3 shows the results of the cost analysis for e-kerosene as well as the cost gap to fossil kerosene. In general, we observe that the costs for e-kerosene is at least three times higher than for fossil kerosene. It is worth noting that the cost gap in aviation is the most significant among the sectors considered in our analysis. The PPA-based process is the most economical in China and least economical in Germany for the same reasons given in section 1.2.

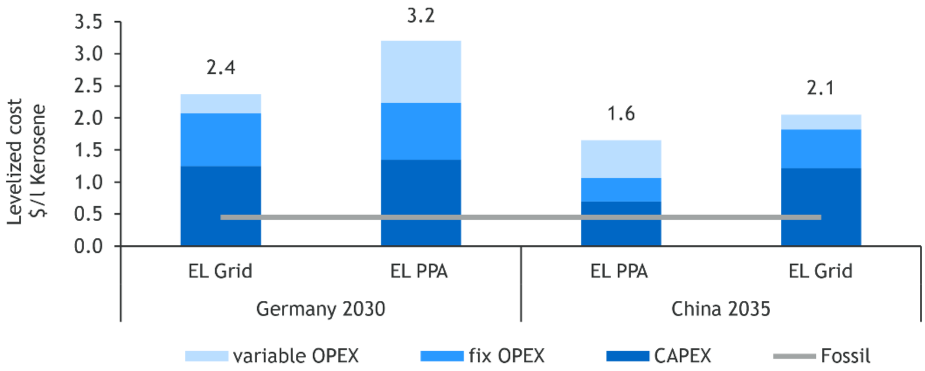

Figure 3: Levelised cost of synthetic kerosene production. Abbreviations: EL Grid - Electrolysis from grid electricity, EL PPA - Electrolysis from PPA of designated renewables

2 Policy instruments to support hydrogen competitiveness

The analysis has revealed that the cost gap between RES-based hydrogen and its conventional counterparts will remain at the business level. To close this cost gap and promote RES-based hydrogen, appropriate policy measures need to be considered. The following analysis focuses on policy instruments that directly or indirectly support the production and utilisation of RES-based hydrogen. After introducing relevant policy measures, the effects and potential interactions of those policy measures as well as their impact on the competitiveness of RES-based hydrogen will be assessed for the chemical, steel production and aviation sectors.

2.1 Comparison of policy instruments

The instruments, "carbon pricing", "carbon contracts for difference (CCfD)", "sector-specific hydrogen quotas", "hydrogen supply contracts" and "subsidies" are introduced, and their effects are presented:

- **Carbon pricing** is an established policy measure in many countries to internalise costs of carbon emissions. It is regarded as a particularly cost-effective instrument, as it relies on market-based allocation of emission reductions (e.g., the European Union Emission Trading System, China National Carbon Trading Scheme). The carbon price applies to direct CO_2 emissions, increasing the operative cost of an emission-intensive process and incentivizing climate-neutral technologies and energy sources (Agora Energiewende and Guidehouse 2021; IRENA 2020; Rissman et al. 2020)
- **CCfDs** aim at closing the gap between the current CO_2 price and the price level required for the cost parity of renewable and conventional technologies. The difference is covered by a public body. Thus, the CCfD decreases the OPEX of RES-based hydrogen. This instrument requires the existence of a carbon pricing mechanism (Jeddi et al. 2021; Öko-Institut 2021; Agora Industrie, FutureCamp, Wuppertal Institut 2021; Kopernikus Projekt Ariadne 2021)
- **Sector-specific hydrogen quotas** are demand-side instruments that oblige a certain party (e.g., suppliers) to buy and supply a defined share of their product from RES-based hydrogen. Quota regulations usually include penalties for non-compliance, setting an implicit maximum willingness to pay for the renewable alternative (Kopernikus Projekt Ariadne 2021; Agora Energiewende and Guidehouse 2021; Öko-Institut 2021)
- **Hydrogen supply contracts** bridge the gap between RES-based hydrogen production costs and the willingness to pay. The measure has been suggested, e.g., by the H2Global initiative in Germany[1]. This instrument is organized as a double-sided auction, whereby an intermediary matches hydrogen supply and demand and covers the remaining cost gap (Wuppertal Institut 2021; Agora Energiewende and Guidehouse 2021).

[1] H2Global Stiftung (2022): https://www.h2-global.de/

- **Sector-specific subsidies** can be demand- or supply-oriented and linked to operative costs or investment costs. Subsidies decrease the cost of renewable hydrogen (supply-side) or increase the willingness to pay (demand-side). Examples are tax or grid fee exemptions or feed-in tariffs for renewable hydrogen (Schlund and Schönfisch 2021).

All these policy instruments can be designed in various ways. For instance, carbon pricing can be designed as a carbon tax or a cap-and-trade system, applied to all sectors or selected industries. A quota e.g., can be designed as a physical blending quota or as tradable certificates. These differences in policy design can impact the instruments' impact on closing the cost gap and their associated advantages and disadvantages. E.g., the advantages of a policy measure can be the risk reduction potential and thus their ability to incentivise private investment. Potential disadvantages of a policy instrument are, for example, the risk of carbon leakage[2] or the risk of oversubsidising, which can result in lock-in effects and market distortion. Table 2 compares various potentials and limitations of the selected policy instruments.

Table 2: Comparison of policy instruments addressing the competitiveness of renewable hydrogen

	Carbon pricing	CCfDs	Sector-specific hydrogen quota	Hydrogen supply contracts	Sector-specific CAPEX-subsidies	Sector-specific OPEX-subsidies
Market-based	yes	yes	no	yes	no	no
Usage of public spending	no	yes	no	yes	yes	yes
Risk reduction potential / Investment incentives	low	medium	high	medium	depends on cost structure	depends on cost structure
Technology openness	yes	yes	none	none	none	none
Risk of oversubsidizing	low	medium	low	medium	high	high
Period of implementation	mid- to long-term	short-term	mid- to long-term	short-term	short-term	short-term
Risk of carbon leakage	high	none	high	none	none	none

Source: Based on (EWI 2022)

2.2 Interdependencies of policy instruments

Public support measures are necessary to significantly ramp-up the production and utilisation of RES-based hydrogen within the next decade (Agora Energiewende and Guidehouse 2021). To facilitate synergies while preventing negative interactions, the potential interdependencies between these policy instruments need to be assessed. Carbon pricing is a cost-efficient policy instrument for closing the cost gap between renewable and carbon-intensive processes. This policy measure has positive synergies with all the other policy instruments. If the CO_2 price remains below the level required for cost-competitiveness of RES-based hydrogen, CCfDs are

[2] Carbon leakage refers to the relocation of CO_2 emissions from countries with ambitious climate measures to countries with less restrictive emission constraints. The introduction of climate policies resulting in additional costs for producers carries the risk that these businesses, in particular from energy-intensive sectors, transfer their production or parts of their production process to countries with laxer regulations. Besides being potentially a concern to a country's industrial competitiveness, this also could increase total emissions.

suitable as a bridging instrument to cover the remaining cost gap. In particular, CCfDs are effective in combination with carbon pricing designed as a cap-and-trade system since CCfDs can address investment insecurities arising from the market dynamics of a cap-and-trade system. A combination of all the discussed policy instruments with a sector-specific hydrogen quota may reduce costs and could thereby dampen the increase in consumer prices. Hydrogen supply contracts are an alternative instrument to CCfDs bridging the cost gap between RES-based hydrogen production costs and the willingness to pay. However, in contrast to CCfDs, hydrogen supply contracts do not require carbon pricing. Thus, hydrogen supply contracts offer an option for supporting selected hydrogen projects in sectors not covered by a carbon pricing mechanism. In the case of hydrogen supply contracts, a combination with direct subsidies may result in double subsidisation and requires careful calibration. In general, subsidies alone or combined with other policy instruments carry an increased risk of oversubsidisation and double subsidisation. CAPEX-subsidies can have a positive effect when high investment costs account for a substantial part of the cost gap between RES-based hydrogen and conventional processes. Sector-specific CAPEX- and OPEX-subsidies can be combined to close the cost gap (Agora Energiewende and Wuppertal Institute 2021; Wuppertal Institut 2020).

To prevent the inefficient application of public spending and potential market distortions, over- or double subsidising hydrogen technologies must be avoided, and combinations of the support measures must be carefully chosen. Table 3 displays applicable combinations of the previously discussed policy instruments. Based on qualitative criteria, these selected combinations of instruments minimise the risk of double subsidisation. Thus, the risk of negative interactions between the policy measures is reduced within each proposed combination, and positive interactions can be facilitated.

Table 3: Proposed combinations of policy instruments which reduce the risk of over- or double subsidisation

Combination 1	Carbon pricing	CCfD	Sector-specific CAPEX-subsidies
Combination 2	Carbon pricing	Hydrogen supply contract	
Combination 3	Carbon pricing	Sector-specific hydrogen quota	Sector-specific OPEX-subsidies
Combination 4	Carbon pricing	Sector-specific CAPEX-subsidies	Sector-specific OPEX-subsidies

Source: Based on (EWI 2022)

2.3 Quantitative effect on the cost gap of selected end-use cases

This section shows the quantitative effect of carbon pricing, and sector-specific CAPEX and OPEX subsidies on the cost gap in Germany and China.

Hydrogen

Figure 4 shows the levelized costs of hydrogen over the carbon footprint of the considered hydrogen production processes. The lines display the marginal abatement costs (MAC) for hydrogen between the most economical and the least carbon-intensive technology. For Germany in 2030, SMR is the most economical technology for hydrogen production. To make RES-based hydrogen from grid electrolysis cost competitive with SMR, policy measures are necessary. A carbon price of 81$/t$CO_2$ can close the cost gap. In China, the MAC are 22$/t$CO_2$ in 2035. A low carbon price would be sufficient to close the cost gap between hydrogen produced via coal gasification and RES-based hydrogen. A CO_2 price puts a significant burden especially on the emission-intensive coal gasification. If the CO_2 price does not reach 22$/t$CO_2$ in China, CCfD can be introduced to cover the remaining cost gap. In case the chemical sector is not covered by a carbon pricing mechanism, hydrogen supply contracts could be used to cover the remaining additional costs of 0.5 $/kg$H_2$ between RES-based hydrogen and hydrogen produced via coal gasification. Alternatively, subsidising CAPEX by 50% will make EL Grid hydrogen cost-competitive and subsidising OPEX by 50% will close the cost gap for EL PPA hydrogen.

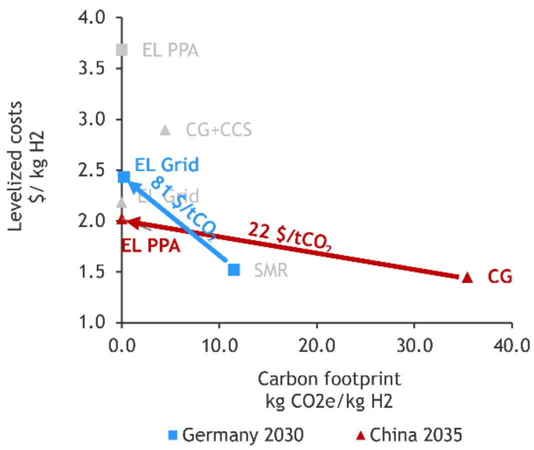

Figure 4: Marginal abatement costs for hydrogen between the most economical and the least carbon-intensive technology

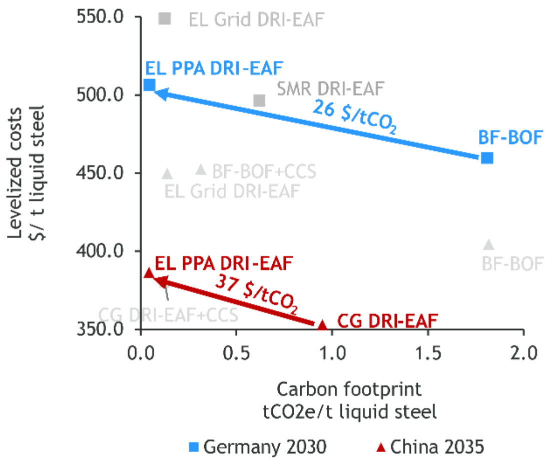

Figure 5: Marginal abatement costs for steel between the most economical and the least carbon-intensive technology

Steel Industry

As Figure 5 shows, a CO_2 price of 40$ can make the EL Grid DRI-EAF cost-competitive with conventional processes in China in 2035. In Germany, the BF-BOF route with a high carbon footprint is the most economical process. A significant carbon footprint reduction comes with marginal abatement costs of 26$/t$CO_2$. Besides, based on our calculations, an OPEX-subsidy of 40% would make EL PPA DRI-EAF cost-competitive in Germany. Since the BF-BOF's costs are calculated as brownfield investments, a CAPEX subsidy alone cannot make hydrogen competitive. For China, in 2035, a CO_2 price of 37 $/t$CO_2$ or alternatively an OPEX subsidy of 30% can result in cost competitiveness of the EL PPA DRI-EAF with the CG DRI-EAF.

Aviation

Due to the differing cost structure of conventional kerosine, which is only determined by the price of fossil kerosene, the effect of policy instruments on the levelized costs of kerosene differs from the two previous cases. Figure 6 shows that the MAC are 765 $/tCO_2$ for Germany and 460 $/tCO_2$ for China. The MAC are considerably higher than in the hydrogen or steel sectors, indicating that a combination of measures would be necessary to close the cost gap. Figure 7 displays the impact of a combination of policy measures on the levelized production costs. Here the CO_2 price increases the levelized production costs of fossil kerosene, the CAPEX-subsidy decreases the costs of EL PPA and EL Grid kerosine, while the OPEX-subsidy only reduces the costs of EL PPA. A CO_2 price of 420 $/tCO_2$ combined with a CAPEX subsidy of 100% for the electrolyser and an OPEX subsidy of 100% on electricity from PPAs would make EL PPA cost-competitive in Germany in 2030. For China, a CO_2 price of 100 $/tCO_2$ combined with a CAPEX subsidy of the electrolyser of 100% and an OPEX subsidy of PPA power of 25% would make EL PPA cost competitive against fossil kerosene. Regulatory interference via an e-kerosine quota for the aviation sector is an alternative to promote the utilisation of hydrogen. An e-kerosine quota of 50% can halve the carbon footprint. The additional costs would be carried by the consumer.

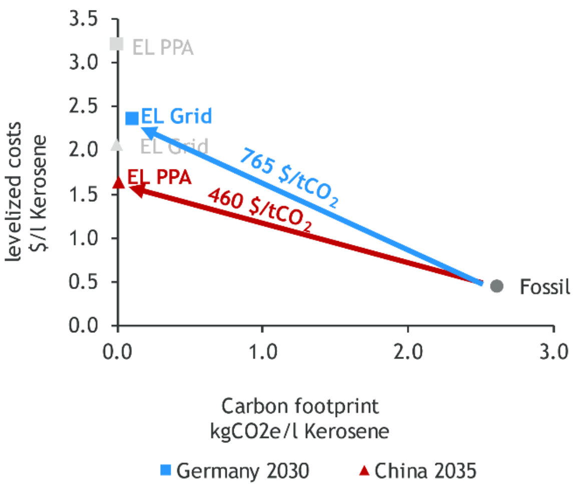

Figure 6: Marginal abatement costs between the most economical and the least carbon intensive process for e-kerosene

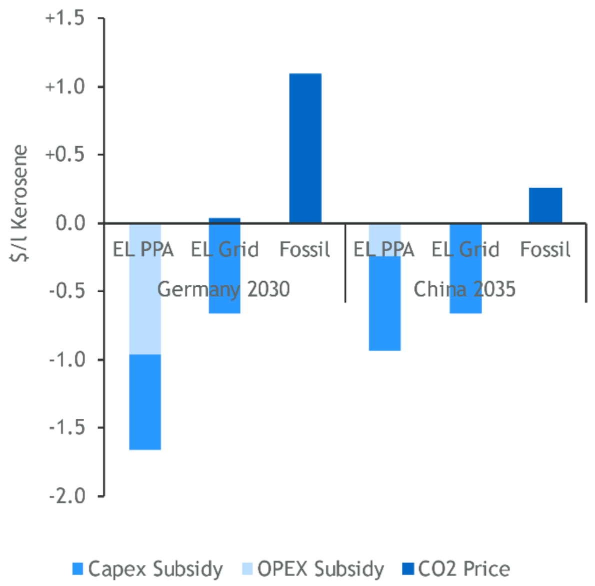

Figure 7: Impact of a combination of policy measures to close the cost gap on the levelized production costs of e-kerosine. Measures for Germany: CO_2 price - 420 $/t, CAPEX subsidy on electrolyser - 100%, OPEX subsidy on electricity from PPAs - 100%. Measures for China: CO2 price 100 $/t, OPEX subsidy on electricity from PPAs - 25%, CAPEX subsidy on electrolyser - 100%

Abbreviation

BF	Blast furnace
BOF	Basic oxygen furnace
CAPEX	Capital expenditures
CCfD	Carbon Contract for Difference
CCS	Carbon capture and storage
CG	Coal gasification
DAC	Direct air capture
DRI	Direct reduced iron
EAF	Electric arc furnace
EL	Electrolysis
FT	Fischer-Tropsch
MAC	Marginal abatement costs
OPEX	Operational expenditures
PPA	Power purchase agreement
RES	Renewable energy sources
SMR	Steam methane reforming
WACC	Weighted average cost of capital

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