Institute of Shipping Economics and Logistics

- Hydrogen -

Logistics is key to the success of the National Hydrogen Strategy

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Executive Summary

Hydrogen is a versatile element in many regards. It can either be used as a commodity for example to produce ammonia or methanol or it can be used as an energy carrier for instance in logistics or in the steel industry. Hydrogen can be produced either from fossil energies by steam reforming („grey hydrogen“) or by electrolysis of water with the use of electrical energy. If electrical energy from renewable sources only is used in the process of electrolysis, so-called „green hydrogen“ is produced. Given this universal applicability, green hydrogen allows for the exploitation of potential cross-sectoral decarbonization. Currently, 99 % of the hydrogen produced worldwide is „grey“, because it is the most economical path of production. To enlarge the share of green hydrogen, production capacities and regulating legal frameworks, for instance in the form of an increased CO_2 price, need to be established. A first step into this direction is the German National Hydrogen Strategy. Here, a demand for at least 90 TWh of hydrogen is projected in the year 2030.

To cover this demand, national production capacities to produce 14 TWh of green hydrogen annually will be arranged. The supply gap of 76 TWh is covered by annual imports of green hydrogen. To ensure these imports, Germany will enter into energy partnerships with sunny countries. This opens up two problematic areas that need to be solved. On the one hand, the drinking water required for the electrolysis is a scarce resource in these countries, which is why the electrolysis of seawater is researched heavily. On the other hand, the hydrogen needs to be transported over large distances. Even liquid hydrogen still has a low density and creates a large transport volume per energy unit; a cubic meter of crude oil roughly contains about four times as much energy as a cubic meter of liquid hydrogen. That means that the supply gap of 76 TWh can be covered by 25,000 loads of the biggest liquid hydrogen carrier available or by 6,000 loads of a crude oil carrier with the same tank volume. Due to some of the cargo boiling off during a long sea voyage, transportation of pure hydrogen by ship is only efficient on short distances to keep these losses at a minimum. Pipelines can be an alternative, if the geographical conditions are met, but they become expensive to build and operate over long distances. An efficient solution for the sea transportation of hydrogen over large distances are so-called e-fuels. To produce them, green hydrogen is transformed in various processes into a liquid like synthetic crude oil or methanol. Conventional means of transport can be used to transport e-fuels, while at the same time, the transport vehicles can be operated climate neutral with the e-fuels. Using e-fuels means accepting conversion losses, but they allow for a short-hand conversion of logistics and transportation to renewable energies by using infrastructure being already available.

An opportunity to reduce conversion losses in the stationary, industrial use of hydrogen is the decentralized production of green hydrogen on-site. Prerequisite for this is a major share of renewable energies in the electricity mix. In the mobile application, for instance in a truck where batteries powered engines are no option due to their weight, the direct use of hydrogen in fuel cells offers a significantly higher development potential. In the long term, fuel cells can avoid conversion losses that occur when only using e-fuels. The prerequisite here is a higher technological readiness level of fuel cells and a well-developed network of filling stations. In the end, different technologies will occupy different niches, and different technical solutions like batteries and fuel cells will coexist side by side.

1 H for Hydrogen

H for hydrogen – the most common chemical element in the universe. H for hope – to meeting the climate targets and for a successful energy transition. H for the hurdles to overcome – in production, transportation, storage and application of hydrogen. H for the high research demand – which the German National Hydrogen Strategy, enacted in June 2020, sets up.

Hydrogen rarely exists in its pure form on earth; most of the time it is rather bound chemically to other elements. Before it is used, the bonds need to be separated. The possible applications to produce hydrogen are manifold. Broken down, the two most common use cases for hydrogen are using the element as a raw material or as an energy carrier. Now, the biggest share of the hydrogen produced worldwide is used as a resource in various industrial processes, such as the production of ammonia, which is used to manufacture fertilizers. Besides the use of hydrogen as feedstock, it has the potential to be used as an energy carrier – although only a minor fraction of the hydrogen is currently used in this way. In logistics, the potentials are huge and versatile: hydrogen and hydrogen products can be used as a fuel in shipping and aviation as well as in rail and road transportation to move goods or people. Many projects are currently evaluating and verifying the potential in these sectors. Hydrogen and its products can also be used as an energy carrier in a small scale in residential areas or in a large scale at industrial end users. In both cases hydrogen can play an important role in the supply of energy, electricity and heating [1], [2].

Therefore, hydrogen is an element, which could find flexible applications in different scenarios and is in use in some already. At this point, another significant aspect of hydrogen comes into play: the production of hydrogen. The biggest share of the hydrogen produced worldwide comes from fossil fuels, but there are possibilities to produce so-called green hydrogen with the use of renewable energies and without emitting any additional CO_2. That means, **green hydrogen gives us the possibility to replace fossil fuel in all important industries and logistics with a sustainable alternative and is therefore a prerequisite for a cross-sectoral decarbonization**. To make use of the decarbonization potentials, the German federal cabinet passed the German National Hydrogen Strategy, a reform package containing 38 measures, on 10th of June 2020. The German National Hydrogen Strategy aims to harmonize environmental sustainability and supply reliability. On the European level, comparable goals in the European Hydrogen Strategy became part of the so-called „Green Deal“. The German National Hydrogen Strategy mentions, that only a small share of the demand for hydrogen will be met by domestic production capacities. Another share shall be achieved by entering into energy partnerships with other EU member states, especially with coastal states of the North and Baltic Sea. The biggest share, however, is planned to be imported from non-EU-states [1], [3], [4].

The scientific research of hydrogen focuses on optimizing the production, the processing and the consumption of hydrogen. Without doubt, this is an important pillar of a hydrogen society. Though, even with the most efficient production and processing, Germany will depend on the imports of large quantities of green hydrogen. That means large quantities of hydrogen will have to be transported, handled and stored. To tackle this challenge on a global and on a domestic level efficiently, holistic logistic concepts are required, that have to be elaborated and that need to be verified. For sure, we know: **the exploration of hydrogen logistics is the key to the German National Hydrogen Strategy's success**.

2 Hydrogen Enables the Diversification of Energy Production

Depending on its production process, hydrogen is mainly classified into grey, blue and green hydrogen. The range of colors could even be enlarged for instance by yellow, brown or turquoise hydrogen. These additional paths of production are usually hybrid processes or even finer differentiations, that can all be associated with one of the three main categories [5], [6].

Grey hydrogen is produced from fossil energy carriers like natural gas or coal. The applied processes are steam reforming or coal gasification. Currently about 99 % of the amount of 74 mln tons of hydrogen produced annually worldwide are manufactured from fossil energy carriers. Depending on the raw material, between 10 and 19 tons of CO_2 are emitted into the atmosphere for each ton of grey hydrogen produced – a catastrophic result [6, pp. 18, 34, 37], [7].

99 % of the annual global production of around 74 million tons of hydrogen are obtained from fossil fuels.

If hydrogen is produced from fossil energy carriers, and the amount of CO_2 emissions into the atmosphere is reduced by technical measures, the produced hydrogen is classified as blue hydrogen. With the means of different so-called carbon capture and storage (CCS) measures up to 90 % of the CO_2, resulting from the production can be captured and stored. CO_2 can be stored for example in the ocean floor, although here the risk persists, that the stored CO_2 leaks into the atmosphere. Therefore, procedures to store CO_2 into stones are the focus of the research. With this procedure, the CO_2 is permanently bound and the risk of CO_2 leaking into the atmosphere can be mitigated and avoided [8]. If only energy from renewable sources is used to produce hydrogen, it is classified as green hydrogen. The most common procedure is the electrolysis. Dedicated machines, so-called electrolyzers, split water into its components oxygen and hydrogen. During the production no CO_2 occurs, the only emission into the atmosphere is oxygen [6, pp. 34, 39], [7], [9].

Only 0.7 % of the worldwide hydrogen production qualify for the classification as blue or green hydrogen. The reason is, that due to a missing tax on CO_2-emissions grey hydrogen production is the most economic path of production, which is why the industry prefers it. Lower costs for electricity from renewable sources would lower the cost disadvantage of green hydrogen and raise its price competitiveness. To lead the German National Hydrogen Strategy to success, changes to the German structure of taxes and fees are required [10], [11]. A lower cost for energy from renewable sources and the increase of the existing tax on CO_2 to 25 € per ton promise a first steering effect. From 2021 on the tax on CO_2 will also include the sectors buildings and transportation [12], [13].

Green hydrogen can be produced from a wide range of renewable sources of energy and is an enabler for a diverse production of energy. Green hydrogen opens up possibilities to decarbonize sectors, that otherwise do not show any potential of decarbonization. Blue Hydrogen has an important role on the path towards a sustainable hydrogen society. Its role is the penetration and diversification of the existing hydrogen market, and to scale up the required infrastructure as well as the industrial production of electrolyzers to pave the way for green hydrogen [14], [15]. If the CO_2 resulting from the production of blue hydrogen cannot be used industrially, it is stored. In any case, a small share of CO_2 is always emitted into the atmosphere during the production of blue hydrogen. In the end, blue hydrogen is highly criticized, because it means a further dependency on fossil energy carriers that need to be transformed with more energy, which again means to emit further CO_2 into the atmosphere. **Blue hydrogen therefore has to be recognized as another bridge technology on the way to a green sustainable hydrogen society only** [16], [17].

3 The National Hydrogen Strategy Requires a Substantial Development of Renewables

For the year 2030 a demand for green hydrogen with a cumulated energy content between 90 and 110 TWh is expected in Germany. That corresponds to an amount between 2.7 and 3.3 mln tons [3]. This demand is forecasted to increase up to 21 mln tons with an energy content of 700 TWh until 2050. To set these numbers into perspective: Germany consumed fossil energy carriers with a cumulated energy content of 2,825 TWh in 2019. 110 TWh of green hydrogen could replace 3,9 % of that amount in 2030 and 700 TWh could replace 24,9 % of these fossil energy carriers in 2050 only [18]. The biggest share of demand for green hydrogen will arise from the sectors industry and transportation [19]. A part of the hydrogen demand will be covered by domestic production capacities. The National Hydrogen Strategy states, that production capacities of 5 GW will be installed until 2030 with a further 5 GW planned until 2040. A production capacity of 5 GW enables the production of hydrogen with an energy content of 14 TWh annually. For the production of this amount of hydrogen 20 TWh of electrical energy[1] are required [3]. With the planned production capacity, Germany will face a supply gap between 76 and 97 TWh in 2030 that has to be closed by importing between 2.3 and 2.9 mln tons of hydrogen per year. The company NOW GmbH that coordinated several funding programs for different Federal Ministries published a study where different scenarios for production capacities of green hydrogen in Germany were simulated and predicts a demand for production capacities between 137 and 275 GW. With these capacities, hydrogen with an energy content ranging from 384 to 770 TWh could be produced annually[2]. In the most optimistic scenario the anticipated demand of 700 TWh in 2050 will be oversupplied by 70 TWh, in the most pessimistic scenario Germany would face a supply gap of 316 TWh, that needs to be closed by importing approximately 9.4 mln tons of green hydrogen [20, pp. 67–76].

MIND THE GAP

The demand for green hydrogen anticipated for 2050 with a total energy content of 700 TWh would be in most optimistic scenario over-satisfied, in the most pessimistic scenario there would be a supply gap of 316 TWh caused by imports 9.4 million tons of hydrogen would have to be closed.

To produce these amounts of green hydrogen, large quantities of electricity from renewable energies are required. In 2019, the total amount of electricity from renewable sources accounted for 240 TWh in Germany. That is about 46 % of the German net electricity production, the remaining share is produced from fossil or nuclear sources [21]. Because the production process for hydrogen consumes energy as well, the amount of energy that is stored as hydrogen in the end is less than the energy delivered as input into the process. The extent of these so-called conversion losses depends on the degree of efficiency of the electrolyzer. At a degree of efficiency of 70 % 1,000 TWh of electricity from

[1] Assumptions: 4,000 full load operating hours per year; efficiency of electrolysis: 70 % [3]

[2] Assumptions: see above

renewable sources produce 700 TWh, the amount of hydrogen that is expected to be required in 2050. That means, Germany needs four times as much renewable electricity in 2050 as today, only to cover the demand of the hydrogen production. Therefore, **the German National Hydrogen Strategy will fail without a drastic, accelerated development of renewable energies**.

Besides the decarbonization of sectors, such as the transport sector that otherwise has hardly any decarbonization potential, hydrogen opens up the possibility, to guarantee the supply of electricity by reconversion during dark doldrums. Dark doldrums describe a period of time, where neither solar activity nor wind power is strong enough to cover the demand for electrical energy. Anyway, the security of supply is more of an additional effect; the major potential of hydrogen lies within the cross-sectoral decarbonization. At this point, the term "primary energy consumption" becomes important. In an economy, energy is not only consumed in the form of electricity but also in the form of other energy carriers like coal, oil or any refined product like diesel or kerosene. Primary energy consumption sums up the amounts of different energy carriers that are consumed in a period, such as a year, by a whole economy. It does not only include primary energy carriers, that are required to produce electrical energy but as well the primary energy carriers that are used to power combustion engines and power plants. Even though renewable energies produce 46 % of the net electrical energy in Germany, their share in the primary energy consumption is significantly smaller. In 2019, the share of renewable energies in the primary energy consumption was only 15 %[3] , the remaining shares are covered by fossil or nuclear sources [22, p. 2]. 72 % of the German primary energy consumption have been covered by imported fossil energy carriers [23]. Even in 2050 Germany will not be energy self-sufficient and is going to import a major share of its energy from other nations, which in itself is not necessarily a drawback [24]. In contrast to today, green hydrogen is an important energy carrier in 2050, and therefore the share of renewables in the primary energy will be much more significant. **Massive imports of green hydrogen are therefore paramount for the success of the German National Hydrogen Strategy**.

To ensure the imports of green hydrogen Germany plans to enter into strategic energy partnerships with other nations on European as well as international level [24]. Specific plans for such energy partnerships do exist with different nations in the west and the south of Africa, where green hydrogen is an actively pursued goal as well. Due to almost constant solar and wind activity, the conditions for the production of renewable electricity are very favorably. In the scope of development projects, the local energy demand and the export demand shall be covered. The energy that is not consumed domestically is planned to be exported as hydrogen or hydrogen products. A large obstacle yet to overcome is that the electrolytic production of hydrogen requires drinking water, which is an already scarce resource in these arid nations. To be able to produce hydrogen in these regions in a sustainable manner, the use of seawater for the electrolysis is a heavily researched topic [25]–[30].

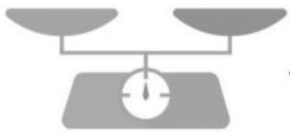
4 The path to a hydrogen society

E-Fuels make use of existing infrastructure to transport green energy

Hydrogen can be transported in different ways: either as pure hydrogen, as hydrogen bound to another element or as hydrogen transformed into a synthetic energy carrier.

[3] Shares in German primary energy consumption 2019: fossil 78 %, renewable 15 %, nuclear 6 %, other 1 % [22]

The transport of pure hydrogen is possible under pressure or in liquefied state. Under pressure, hydrogen is transported in pipelines or in pressurized containers. The pressure in a pipelines is scaled between 30 and 80 bar. Pipelines are very efficient to transport large quantities of gas. However, their construction and operation is cost intensive over large distances. In pressurized containers with up to 500 bar the compression of the gas is much larger. The transportation in pressurized containers has the advantage that the containers can be transported with common infrastructures such as trucks, railroad or container vessels. Prerequisites are an appropriate number of these containers available and their authorized approval. For example the development of specialized containers on a 40-foot-frame is finalized and is only awaiting official approval [31, pp. 16–17]. High-volume hydrogen pressure vessels are highly qualified for the storage for example on factory sites, where space is not an issue [32]. Given that geographical conditions are met, existing salt caverns can be a good means to store hydrogen as well [33]. If cooled down to – 253 °C, hydrogen becomes liquid[4] and can be transported in specialized cryotanks. By changing the physical state to a fluid, the hydrogen's density is maximized and a bigger mass of hydrogen and a larger amount of energy can be stored at the same volume compared to gaseous hydrogen. Due to the cargo warming up during a long sea voyage a part of the cargo becomes gaseous again by boiling off. This so-called boil-off gas can lead to an increase of the tank pressure and become a threat to the tank's integrity. The first specialized liquid hydrogen carrier[5] that is transporting grey hydrogen since 2020 from Australia to Japan, burns this boil-off gas [34].



1 cubic meter of liquid hydrogen weighs 70.8 kg.

Hydrogen can also be transported by bonding the element to another medium, such as a liquid organic hydrogen carrier (LOHC). In a chemical reaction the hydrogen is bound to a LOHC and is separated again just before use. The bonding and the separation are highly energy-intensive, because the process requires pressures up to 50 bar and temperatures exceeding 400 °C [35]. Less energy is required if the hydrogen is not bound to a LOHC but to a metal hydride. Metal hydride storage assets are very heavy due to their materials and are rather qualified for a stationary use. Also the raw materials can be quite expensive [36], [37].

Another possibility for the transportation is the transformation of hydrogen into another synthetic energy carrier. These procedures are termed as Power-to-Gas (PtG) and Power-to-Liquid (PtL) that are summed up to Power-to-X (PtX). PtG processes synthesize for example methane or ammonia. Methane being produced in this way is called synthetic natural gas (SNG) that can be liquefied (SLNG) or compressed (SCNG). Products of PtL-processes are for instance methanol or synthetic crude oil, so-called e-crude. E-crude is produced for example with the so-called Fischer-Tropsch-Synthesis. Hydrocracking refines the product into naphtha, diesel, kerosene or gasoline. Synthetic fuels, that are the result of a PtX-process are called e-fuels [38], [39]. They have the same physical and chemical properties as their fossil counterparts and can be stored, transported and used in the same ways [40]. **Therefore, e-fuels**

4 For comparison: liquefied natural gas (LNG) is transported at temperatures around – 160 °C

5 L H_2-Carrier Suiso Frontier carries up to 1,250 m^3 liquid hydrogen. At – 253 °C that translates to 88.75 t liquid hydrogen

introduce the possibility to keep using existing infrastructure and proven logistics concepts to store, transport and make use of large amounts of renewable energies.

Only E-Fuels Enable Economic Import over Large Distances at the Moment

Hydrogen has a high gravimetric density with 33.33 kWh/kg. In contrast, the volumetric energy density, even in liquefied state, is low. A requirement for the transportation of pure hydrogen in compressed or liquefied form are large volumes of the tanks and complex technical solutions to reduce or re-liquefy boil-off gas, only to transport comparably small amounts of energy. E-fuels have a significantly lower gravimetric density than pure hydrogen, but the obtainable relation between volume and energy density is much more favorable due to the mass density of the e-fuels.

Table 1 lists different properties of liquid hydrogen and some e-fuels that are most relevant for logistics. For each energy carrier it is demonstrated how much energy could be transported with a cargo load of a ship of an existing and common size.

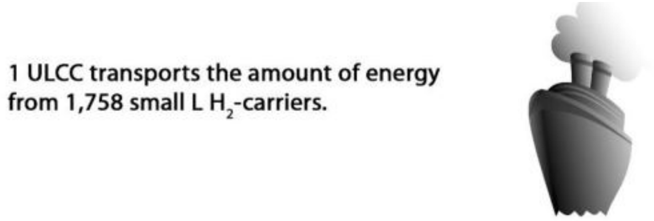
Table 1: Logistics of hydrogen and hydrogen products

		L H_2	SLNG	Ammonia	Methanol	E-Crude	E-Diesel
Substantial properties	Density [kg/m³]	70.8	450.0	600.0	792.0	870.0	845.0
	Energy density [kWh/kg]	33.3	13.9	5.2	5.5	11.6	11.9
	Energy density [kWh/m³]	2,359	6,251	3,120	4,332	10,092	10,056
Potential means of transport	Vessel Name	Suiso Frontier	Mozah	Yara Kara	Taranaki Sun	FSO Asia	LR2 Eternity
	Vessel Type	L H_2-Carrier	LNG-Carrier	LPG Tanker	LPG Tanker	Ultra Large Crude Carrier	Product Tanker
	Tank Volume [m³]	1,250	266,000	20,600	55,330	513,683	115,572
	Transported mass [t][6]	84	113,715	11,742	41,630	424,559	87,835
	Transported Energy [GWh]	3	1,629	63	235	5,080	1,139

The table demonstrates that at the moment **a large scaled import of pure hydrogen over large distances cannot be conducted efficiently without the use of e-fuels** because the available means of transport allow only to carry a small amount of energy in the form of hydrogen. Even under the assumption that L H_2-carriers are developed further and it becomes possible, to transport more mass and energy of liquid hydrogen, the transportation of e-fuels always enable the transport of more energy with the same tank volume and do not even require the development of new infrastructure.

[6] Assumption: Tanks are filled up to 98 %, to account for boil-off gas and expansion of the cargo

To cover the supply gap in 2030 of at least 2.3 mln tons green hydrogen, 25,000 annual cargo loads of hydrogen with a L H_2-carrier of the size of a Suiso Frontier or 15 annual cargo loads of e-crude with a ULCC of the size of a FSO Asia would need to be handled, to cover the energy demand.



Hydrogen Products Enable Fast Measureable Success

By using existing infrastructure, e-fuels enable immediately switching logistics and transportation to green and CO_2 neutral energies.

For example there are plans to produce green hydrogen from solar power [40]. In a thought experiment, sustainable hydrogen is produced from renewable energies in a sunny country and is transformed on-site into a synthetic energy carrier such as e-crude. A common tanker without any retrofit transports the e-crude to Europe. Here it is refined into an e-fuel in a common refinery and the e-fuel is transported with regular trucks to the gas station, where the end user can fill his car with a climate neutral e-fuel. By using e-crude and e-fuels, the complete supply chain from the manufacturer to the end user is operated completely on renewable energies. Therefore, e-fuels are a short and middle term bridge technology to operate transportation and logistics in a climate neutral way. In the long term it is expected that more efficient fuel cells and batteries will become available and that they will replace e-fuels. But even in the long term e-fuels will fill in a niche in logistics, where battery or fuel cell technologies cannot be operated due to restrictions of dimensions or weight [41], [42].

A prompt market introduction of e-fuels is hindered by the comparably high costs for the production and transportation per energy unit of the refined product. In a contemporary study, fuel prices for 2050 were projected per energy unit: 29 EUR/MWh[7] for fossil LNG, 39 EUR/MWh for fossil VLSFO/MGO, 123 EUR/MWh for green hydrogen and 162 EUR/MWh for synthetic diesel. Another study expects a price of 73 EUR/MWh for fossil fuels in 2050 and between 80 and 140 EUR/MWh for e-fuels [41], [43]. The industrial consortium Norsk e-Fuel plans to build a production facility in Norway to produce synthetic kerosene. Beginning in 2023, 10,000 m^3 of kerosene[8] shall be produced annually until 2026 when production is raised to 100,000 m^3 per year. The consortium expects a selling price of 3.5 € in 2023, which will be lowered to 1.2 € in the long term. Converted to energy units this results in 369 €/MWh in 2023 and 126 €/MWh with a perspective. That shows, that even in the long run, synthetic kerosene is much more expensive than its fossil counterpart with a price of around 45 €/MWh in January 2020 [44], [45].

In most scenarios, e-fuels are significantly more expensive than their fossil pendants. An earlier cost leadership can only be achieved at the expense of a higher price on CO_2 to about 200 € per ton and a restructuring of other fees and taxes [10], [46], [47].

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7 Exchange rate 25.09.2020: 1 USD ≈ 0,86 EUR

8 An Airbus A350 has a tank volume of 150 m^3. 10.000 m^3 kerosene are about 65 tank fillings of this type of airplane.

Another future market for e-crude is the part of the petrochemical industry, that produces plastics and polymers. The raw materials for their production are mainly fossil naphtha and natural gas that could both be replaced by their sustainable synthetic counterparts. Oil majors are expecting, that from 2035 the efficiency of engines and alternative fuels will achieve such a high level that the demand for fossil fuels will stagnate; however they expect a growing demand for plastics and polymers and a coherently growing demand for raw materials from the petrochemical industry worldwide [48]–[50]. Under the assumption that green hydrogen is produced in sufficient quantities, there is a possibility that this sector can also be decarbonized by supplying synthetic hydrogen based raw materials.

Direct use of Hydrogen Offers a Significantly Higher Development Potential

In the previous chapter it was demonstrated that e-fuels offer a short-term possibility for decarbonization of many sectors by operating existing infrastructure with hydrogen products. In that case, the existing vehicles and infrastructure already create a demand that is far larger than it can be covered by existing production capacities. A further expansion of the existing capacities therefore will meet a guaranteed demand, and many sectors can gradually switch to a climate neutral operation.

In the meantime, the technical development of fuel cell based drives will improve. **In the long term, the direct use of hydrogen with the use of fuel cells offers a significantly higher development potential**. Vehicles that are transporting people and goods, can be operated on fuel cells and electric motors instead of a combustion engine. In a fuel cell the hydrogen reacts with oxygen, the only emission is water. During this process electrical energy is produced, that powers an electric motor via a battery buffer. Prerequisite for the operation of vehicles with pure hydrogen is the availability of a filling station infrastructure [51]. Fuel cells cannot be applied in vehicles only but also everywhere, where a demand for electrical energy exists. Especially stationary units can be scaled significantly larger than mobile units, because the dimensions of the vehicle do not limit the size of a hydrogen tank. Hydrogen fuel cells are a solution to bridge dark-doldrums by reconversion of the hydrogen into electrical energy in newly built power plants. This only requires that a sufficient amount of hydrogen is stored beforehand [52, p. 30].

5%

About 5 % of all CO_2 emissions in Germany are caused by the steel industry.

Other possibilities for the direct use of hydrogen can be seen in the manufacturing sectors. About 5 % of the CO_2 emitted in Germany annually can be traced back to the steel industry [53], [54]. This share can be reduced by utilizing green hydrogen as a reducing agent. A demand of 2.4 mln tons of hydrogen with an energy content of 80 TWh by the German steel industry is expected in 2050 [3].

In this chapter different means of hydrogen transport have been presented. It was also clarified, that each transformation requires an amount of energy, which leads to so-called conversion losses. To avoid these conversion losses, hydrogen has to be transported in its pure form and only over short distances. **Therefore, the local decentralized production of hydrogen on-site offers the most efficient use potential** [55]. The local production reduces transportation and conversion losses to a minimum. For a local production, renewable energies have to make up a significantly larger share in the production of electrical energy [12].

The Coexistence of Different Hydrogen Technologies

In many industrial sectors like manufacturing sectors, the possibilities to use green hydrogen are obvious and it is expected, that the direct use of hydrogen will prove itself as the most efficient solution. Other sectors, like for example transportation and logistics show a wide range of different use cases such as the use of hydrogen products.

For example in shipping: small workboats in the port area could be supplied by batteries, because their operating times are short, the energy demand is small, the operation is restricted and the boat could be charged at its berth [56]. An inland waterway vessel that is powered by batteries is more difficult to realize. Even though the energy demand might be manageable, the operation area and time are significantly larger. An inland waterway vessel might therefore be more suited for an electric propulsion powered by a fuel cell. Related projects like for example the retrofit of a push boat with a fuel cell are currently in the realization phase [57]. Both types of drive are not suited for larger sea-going vessels. Though there are cruise vessels that operate on a battery-powered engine during maneuvering, a longer operation with batteries is not possible due to the accumulated weight of the required batteries. In addition, a fuel cell powered engine cannot be realized up to now due to the low volumetric energy density of liquid hydrogen. To carry the same amount of energy as it is carried with regular bunker oil, the tank volume would have to be increased by factor five if compared to HFO or factor three when compared to LNG. To operate sea-going vessels on green energies, sustainably produced e-fuels are required [58]–[60]. An operation depending on fuel cells and green hydrogen could become a long-term goal, if the efficiency and the technologies of the drive train and the tanks are improved and a higher technological readiness level is achieved. Cooperation projects and letters of intent for the development of fuel cell systems for sea-going vessels have already been signed [61].

This example signifies, that there will not be a singular technical solution matching all requirements, and that there will rather be a bunch of different technical solutions that will cover different niches and areas of operation instead. A comparable situation will not only arise in shipping, but also in the road and rail transportation as well as in aviation [51], [62], [63]. Especially in railroad logistics, this concept will only find application on routes, that cannot be electrified or that are used for shunting [64], [65]. We know for sure, that **there will not be only one solution to use hydrogen, rather a lot of different technologies, which will coexist on the same level in the medium-term future**.

5 Conclusion

The German National Hydrogen Strategy from June 2020 presents a path how Germany can transform itself into a hydrogen society. Besides different possibilities of the decarbonization of many sectors, the funding of industry and research is an integral part of the strategy.

To cover the growing demand for green hydrogen in the long-term, the establishment of extensive domestic production capacities is planned. To produce considerable amounts of green hydrogen in Germany, it is required, that renewable energies and their share in electricity generation are expanded drastically. However, even with a significantly enlarged production capacity, large amounts of energy must be imported from other states in the form of hydrogen or hydrogen products. For 2030, it has been estimated, that at least 2.3 mln tons of green hydrogen with an energy content of 76 TWh have to be imported into Germany. To set these numbers into a perspective: this amount of energy corresponds to the theoretical energy consumption of 19 mln 4-person-households[9].

To import these amounts of energy carriers and distribute them within Germany, holistic concepts for the transportation, the storage and the handling being not yet available, are to be elaborated and need to be verified. Additionally the quantity structures of the hydrogen demand of all sectors need to be investigated concerning their respective transportation and storage capabilities.

2030 there will be 76 TWh of green hydrogen imported to Germany. This corresponds to the average annual electicity consumption of 19 million 4-person households.

Due to the currently available means of transport, the import of large amounts of energy in the form of hydrogen is inefficient. The transportation of hydrogen products such as e-crude, synthetic natural gas or synthetic ammonia by using existing infrastructure and common vehicles is much more efficient.

Potentials of the application of hydrogen and hydrogen products for different end users should be verified. Hydrogen products such as e-fuels enable a short-term reduction of additional CO_2 emissions, but other concepts will be more efficient and ecological in the long term. On the one hand, that is the usage of new synthetic fuels such as ammonia or methanol. On the other hand, engines powered by batteries or fuel cells do have a great potential in certain areas as well. All these potentials have to be studied in detail and need to be verified by life cycle assessments.

The German National Hydrogen Strategy advertises the successful energy transition as the unification of environmental sustainability, guaranteed supply and affordability. To achieve environmental sustainability, a massive development of renewable energy is required in Germany and in exporting countries. Guarantee of supply requires the development of extensive production capacities of green hydrogen and the agreement into new international energy partnerships. Affordability is accomplished by restructuring the fees and taxes around a CO_2 price to level out price differences between renewable and fossil fuels. All this is possible and requires intense studies of the different sectors and the development of logistics concepts. Logistics is the key to the German National Hydrogen Strategy's success.

[9] Annual power consumption of an average 4-person-household in a single-family house without electric water heating: 4.000 kWh/year [66]

6 Table of Literature

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