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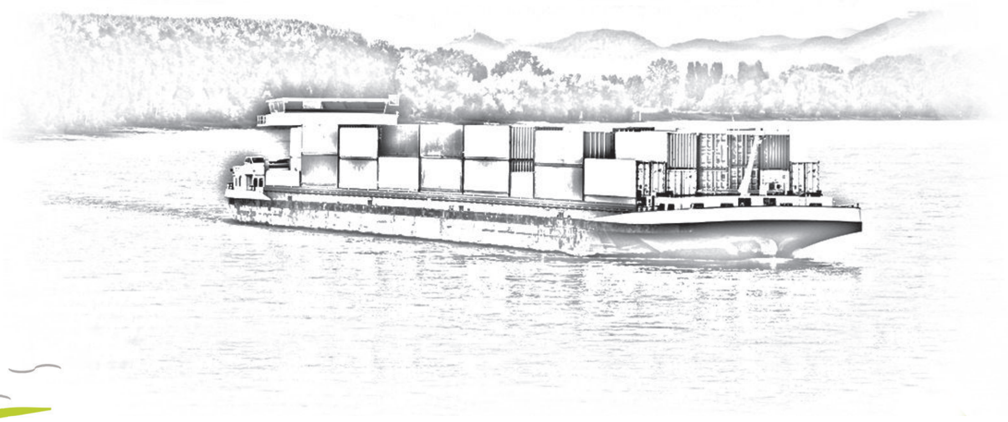
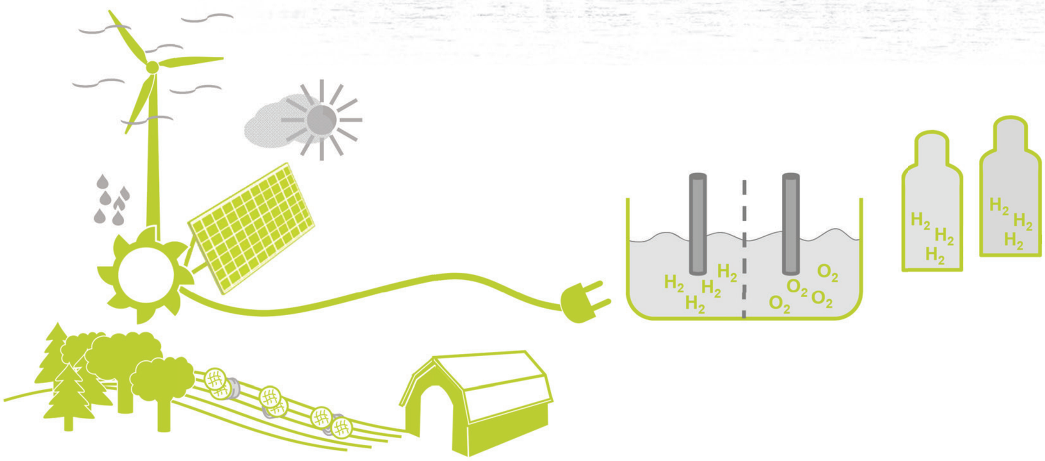
Perspectives for the

Use of Hydrogen as Fuel in Inland Shipping





A Feasibility Study

MariGreen
Maritime Innovations in Green Technologies

Perspectives for the Use of Hydrogen as Fuel in Inland Shipping
A Feasibility Study

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Within the project

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Abstract

After emission limits for particulates, CO, HC and NO_x have been tightened in the last years, this trend is expected to continue. In order to comply with the new standards, alternative propulsions systems as well as fuels should be considered. From this point of view, hydrogen is very promising, because it allows for a significant reduction of emissions.

In this study, current technical alternatives are compared and contrasted with the special requirements in inland shipping. To do so, several stages from hydrogen production and distribution to the storage and conversion of hydrogen onboard the vessel are covered.

First, various ways of hydrogen production are explained including an analysis of the local distribution of production sites. With special regard to the transport to the harbor, the potentials are elaborated and compared to current and predicted future requirements regarding a supply infrastructure. In a next step, the features of various hydrogen storage technologies are presented. These include storage in compressed gaseous and liquid form as well as Liquid Organic Hydrogen Carriers (LOHC) and metal hydride storages. In the same way the characteristics of relevant fuel cell types are introduced as well as the particularities and challenges regarding the usage of hydrogen in internal combustion engines.

These analyses in combination with a definition of the requirements regarding the constructional integration and the operation of these technologies onboard ships are the basis for a rough dimensioning of the hydrogen storage system for four exemplary ships (cargo vessel, pushed convoy, cabin vessel, Rhine ferry) that can be considered representative for their respective kind. For every type of vessel, the combinations of the selected energy storage and conversion technologies are evaluated systematically based on typical operational profiles.

In this study also instruction and training concepts for several fields and tasks as well as occupational groups are introduced. Finally, the relevant legal situation including identified gaps is presented and strategies are pointed out how hydrogen technologies can be established in inland shipping.

Key words: hydrogen, inland shipping, hydrogen storage, combustion engine, fuel cell

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Nomenclature

λ	combustion air ratio	-
ρ	density	kg/m^3
c_p	specific heat capacity	J/(kg*K)

Abbreviations and Acronyms

AEL	alkaline electrolysis
AIP	air independent propulsion
BMVI	Bundesministerium für Verkehr und digitale Infrastruktur
BV	Bureau Veritas
CCGT	Combined Cycle Gas Turbine
CCNR	Central Commission for the Navigation on the Rhine
CESNI	Comité Européen pour l'Élaboration de Standards dans le Domaine de Navigation Intérieure
CH_2	compressed hydrogen
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
DME	dimethyl ether
DNV	Det Norske Veritas
ECMT	European Conference of Ministers of Transport
EFRE	Europäischer Fond für Regionale Entwicklung
EGR	exhaust gas recirculation
EIB	Innovation Fund or the European Investment Bank
ESD	electrostatic discharge protected
ETS	Emission Trading System
EU	European
EX-Zone	hazardous area
FC	fuel cell
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
GHLV	gaseous hydrogen land vehicle
GL	Germanischer Lloyd
H_2	hydrogen
H_2O	Water
HC	unburnt Hydrocarbons
HTEL	high temperature electrolysis
HTPEM	high temperature polymeric electrolyte membrane
ICE	internal combustion engine
IEC	International Electrotechnical Commission
IGF-Code	International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels
IMO	International Maritime Organiziation
ISO	Internationale Organisation für Normung
IVR	International Association of the Rhine Ship Register
IWP	engines above 19 kW used for direct or indirect propulsion of inland waterway vessels
IWT	inland waterway transportation

KOH	potassium hydroxide
LH_2	liquid hydrogen
LHV	electrical efficiency
LNG	liquid natural gas
LOHC	liquid organic hydrogen carriers
LR	Lloyds Register
MCFC	molten carbonate fuel cell
MEA	membrane-electrode assemblies
MeOH	methanol
MLI	multilayer insulation
NaBH4	sodium borohydride
NAPE	Nationaler Aktionsplan Energieeffizienz
NG	natural gas
NH_3	ammonia
NIP	National Innovation Program Hydrogen and Fuel Cell Technology
NO_x	nitrogen oxides
NST2007	Einheitliches Güterverzeichnis für die Verkehrsstatistik
O_2	oxygen
P2X	Power-to-X
PAFC	phosphoric acid fuel cell
PEFC	polymer electrolyte fuel cell
PEM	proton exchange membrane
PEMEL	proton exchange membrane electrolysis
PEMFC	polymer electrolyte membrane fuel cell
PM	particulate emission mass
PN	particulate emission number
R&D	research and developement
SAE	Society of Automotive Engineers
SOFC	solid oxide fuel cells
TEU	Twenty-foot Equivalent Unit
TRL	Technology Readiness Level
TTW	tank-to-wheel
VBW	The Association for European Inland Navigation and Waterways
VKA	The Institute for Combustion Engines
WTT	well-to-tank
WTW	well-to-wheel

1 Project Background, Goal, Partners and Funding

Within the project MariGreen – Maritime Innovations in Green Technologies – funded by Interreg, 65 partners from Germany and the Netherlands join their forces to develop and demonstrate innovations for green and low-emission shipping. In addition to the 12 sub-projects, which are mainly concerned with the use of liquid natural gas (LNG) and wind as power sources for ship propulsion, the present feasibility study deals with the use of hydrogen in inland waterway transport. Whereas LNG is being introduced as a transition fuel to reduce emissions in the near future, hydrogen offers the potential to achieve the long-term goal of emission free-mobility.

Motivated by the increasing pressure towards a green mobility sector, in this study, the current technical possibilities and perspectives of the hydrogen technology in inland shipping are demonstrated.

After a general introduction to inland shipping in Europe (chapter 2), an overview of existent hydrogen technology applications in inland shipping and possibilities of technology transfer from other sectors are presented (chapter 3). Current technical alternatives are compared and contrasted with the special requirements in inland shipping. To do so, several stages of the hydrogen, from its production and distribution to the storage and conversion onboard the vessel are covered.

First, several ways of hydrogen production are explained including an analysis of the local distribution of production sites. With special regard to the transport to the harbor, the potentials are elaborated and compared to current and predicted future requirements regarding a supply infrastructure (sections 4.1 and 4.2). In a next step, the features of various hydrogen storage technologies are presented. These include storage in compressed gaseous and liquid form as well as liquid organic hydrogen carriers (LOHC) and metal hydride storages (section 4.3). In the same way the characteristics of relevant fuel cell types are introduced as well as the particularities and challenges regarding the usage of hydrogen in internal combustion engines (section 4.4).

These analyses in combination with a definition of the requirements regarding the constructional integration and the operation of these technologies onboard ships are the basis for a rough dimensioning of the storage for four exemplary ships (cargo vessel, pushed convoy, cabin vessel, Rhine ferry) that can be considered representative for their respective kind. For every type of vessel the combinations of the selected energy storage and conversion technologies are evaluated systematically (section 4.5).

In this study also instruction and training concepts for several fields and tasks as well as occupational groups are introduced. Finally, the relevant legal situation including identified gaps is presented and strategies are pointed out how hydrogen technologies can be established in inland shipping. (chapters 5 to 8)

Fig. 1.1: Logos of the partners involved in this feasibility study

In this feasibility study the partners shown in Fig. 1.1 were involved. The input data to the analyses in this study are based on literature research and own investigations of the partners. The main contributions of the partners are as follows.

DST provided statistical data and information about IWT, hydrogen projects in the maritime sector, hydrogen infrastructure, training for hydrogen applications, operational profiles and the legal situation of implementation of hydrogen technologies.

TU Delft, TU Eindhoven and the company Electric Ship Facilities provided information about metal hydride hydrogen storage and fuel cell technologies.

abh INGENIEUR-TECHNIK GmbH collected detailed information about storage and hydrogen powered internal combustion engines. The latter part was achieved in cooperation with the Institute for Combustion Engines (VKA) of RWTH Aachen University

The topic of education and training in the context with hydrogen on ships was covered by the Hochschule Emden/Leer.

The Association for European Inland Navigation and Waterways (VBW) provided information about the legal framework and wrote the action guidance.

The Institute for Combustion Engines (VKA) of RWTH Aachen University scanned, sorted and assessed the information provided by the partners. Where necessary, further investigations were carried out. VKA also executed the exemplary operational calculations and the evaluation of technical alternatives based on requirements jointly defined by the partners. Moreover, VKA ensured the coherence of all information and was responsible for creating this report.

2 Inland Water Way Transportation

The Netherlands, Belgium, Germany and France – for the Rhine region in particular – have a major interest in maintaining and expanding inland waterway transport as an important part of the logistics chain. Adhering to current and future exhaust emission limit values is therefore a key objective. That is why necessary changes in propulsion and fuel technology are given high priority in order to make inland waterway transport sustainable and at the same time to maintain its competitiveness.

In this chapter, an overview is given of the European inland waterway network, goods and quantities transported, emissions and the inland waterway fleet.

2.1 Inland waterway network

The European inland waterways cover a length of over 41,500 kilometers, divided into navigable rivers and lakes and artificial canals. In Fig. 2.1 the length of inland waterways is shown by country. Due to its geographical environment, Finland has the longest network of navigable waterways, closely followed by Germany with almost 8000 km. Despite the Netherlands' small area, the length of its waterways amounts to more than 6000 km. Whereas in Finland, Poland, Hungary, Romania, and Bulgaria, the vast majority of water ways is on natural water bodies, in Germany about one fourth are canals and in the Netherlands, France, Italy and Belgium this fraction is even more than 50 %.

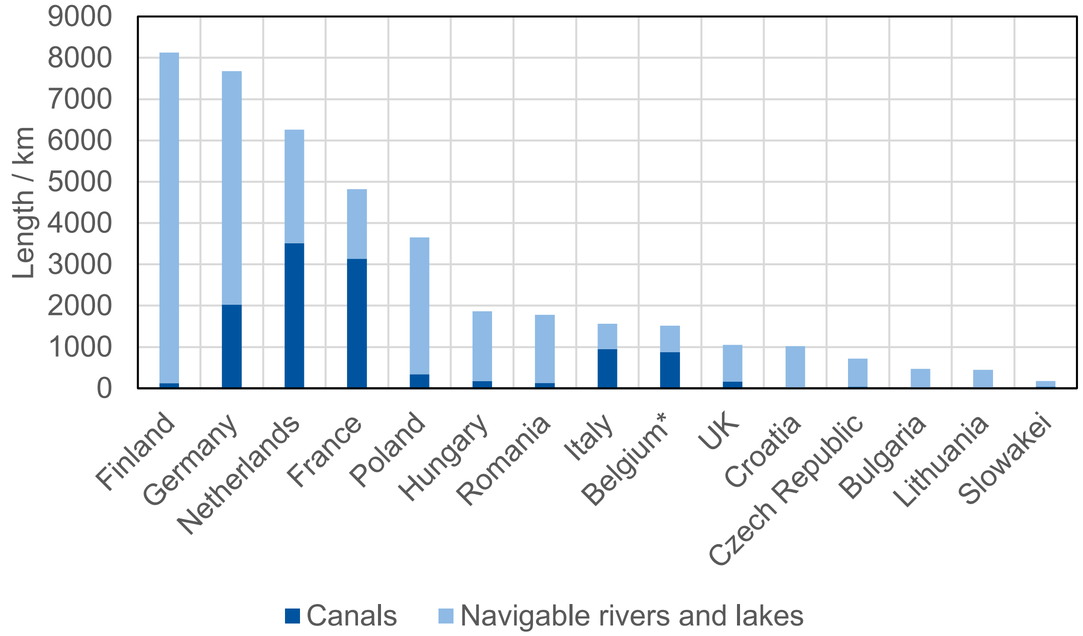

Fig. 2.1: Inland waterways in Europe in 2015 (*Data from 2008) [Dat15]

2.2 Inland waterway transportation

The modal split in freight transport in the European (EU) countries in which inland waterway transportation (IWT) is a considerable factor is shown in Fig. 2.2 for 2015. The share of inland waterway transportation as percentage of ton-kilometers is highest in the Netherlands, followed in decreasing order by Romania, Bulgaria and Belgium. This can be reduced to the three main regions Rhine, Danube and France with its rivers and canals. In particular, the Rhine is a vital inland connection of the Dutch and Belgian seaports. For the other EU countries IWT plays only a minor role which is why they are not considered throughout this study.

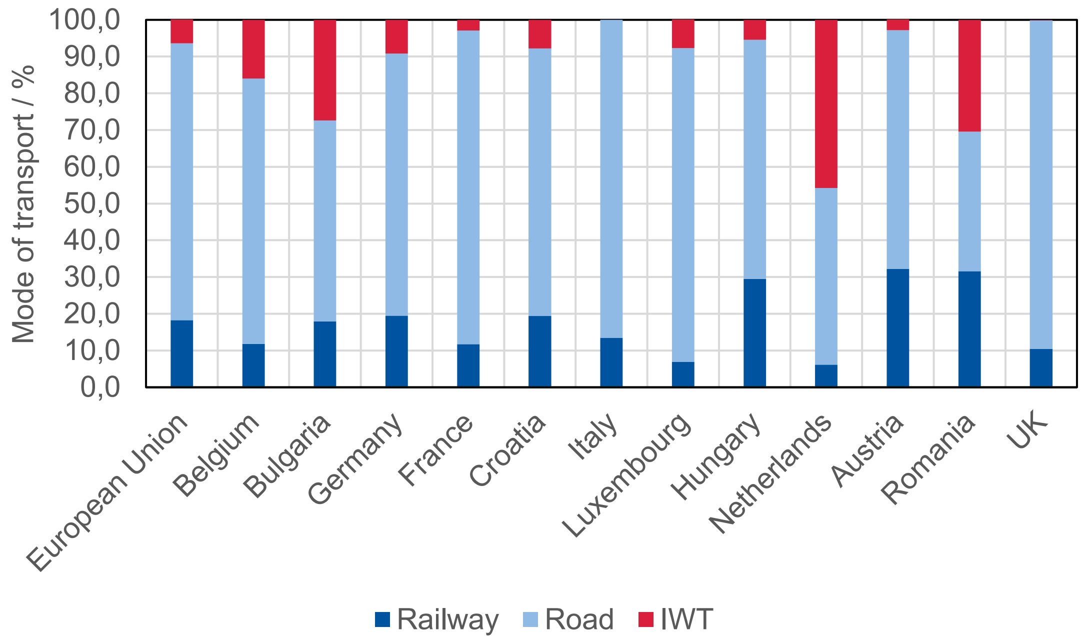

Fig. 2.2: Modal split of freight transport per country as percentage of ton-kilometers in 2015 [Dat15]

The development of annual freight transport in inland navigation in the previously selected countries from 1982 to 2016 is shown in Fig. 2.3. Whereas no clear trend can be detected for France, and for Germany the transport capacity has even been decreasing in recent years after a steady increase in the years before, the general trend for the other countries, Belgium, the Netherlands, Bulgaria and Romania as well as the entire EU clearly indicates a gain in transport capacities.

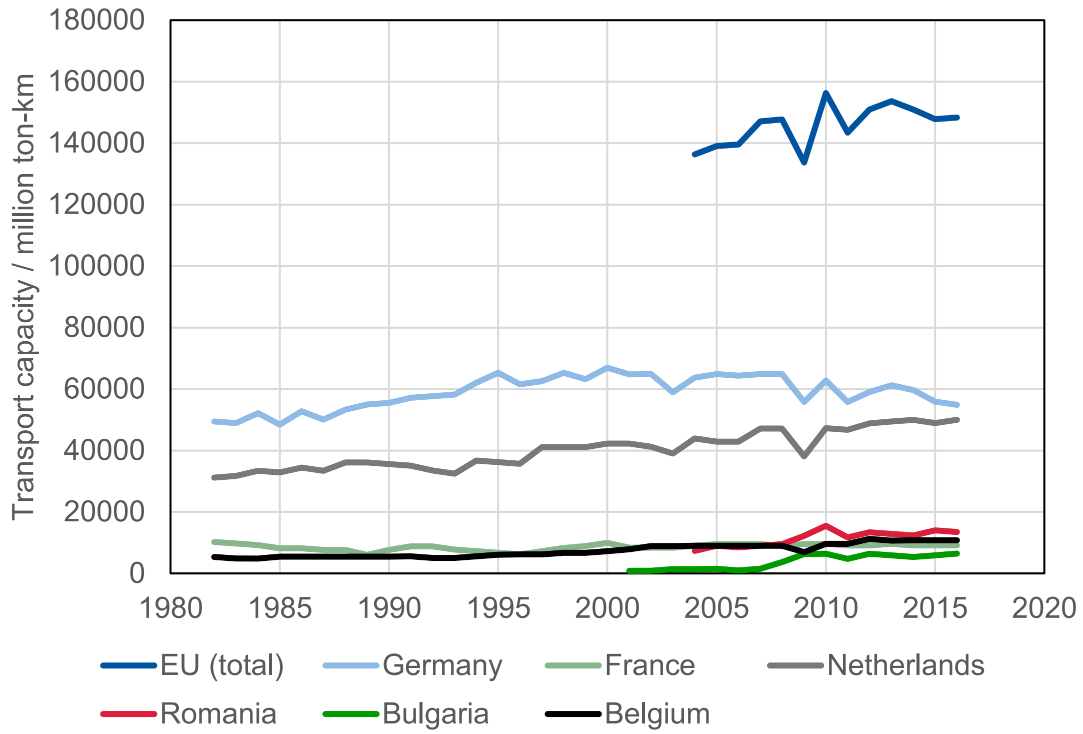

Fig. 2.3: Development of freight transport of inland waterways for countries over 1000 ton-km [Dat15]

A general classification and the weight distribution of goods transported on inland waterway vessels in the countries bordering the Rhine are presented in Table 2.1 and Fig. 2.4. This includes the Central Commission for the Navigation on the Rhine (CCNR) member states except for Switzerland. The order of countries differs to that in Fig. 2.3 because of the different units. This favors countries with transportation of heavy goods for short distances.

The Netherlands have by far the highest amount of goods transported followed by Germany, Belgium and France. It is clearly visible that in Germany, the Netherlands and France metal ores and other mining and quarrying products are by far the most important type of goods. They are followed by coke and refined products in the Netherlands and Germany and agricultural, forestry and fishing products in France. Coal, crude oil and natural gas as well as chemical products are other important categories. With weight being the base, commodities that are inherently transported in bulk masses dominate the statistics. A large portion of the unidentified goods can be traced back to container transport adding up to a considerable share in transport the Rhine area.

Table 2.1: Classification of goods according to NST2007 [Dat15]

Divi-son	Description
D01	Products of agriculture, hunting, and forestry; fish and other fishing products
D02	Coal and lignite; crude petroleum and natural gas
D03	Metal ores and other mining and quarrying products; peat; uranium and thorium ores
D04	Food products, beverages and tobacco
D05	Textiles and textile products; leather and leather products
D06	Wood and products of wood and cork (except furniture); articles of straw and plaiting materials; pulp, paper and paper products; printed matter and recorded media
D07	Coke and refined petroleum products
D08	Chemicals, chemical products, and man-made fibres; rubber and plastic products; nuclear fuel
D09	Other non-metallic mineral products
D10	Basic metals: fabricated metal products, except machinery and equipment
D11	Machinery and equipment n.e.c.; office machinery and computers; electrical machinery and apparatus n.e.c; radio, television and communication equipment and apparatus; medical, precision and optical instruments; watches and clocks
D12	Transport equipment
D13	Furniture; other manufactured goods n.e.c
D14	Secondary raw materials; municipal wastes and other wastes
D15	Mail, parcels
D16	Equipment and material utilized in the transport of goods
D17	Goods moved in the course of household and office removals; baggage and articles accompanying travellers; motor vehicles being moved for repair; other non-market goods n.e.c.
D18	Grouped goods: a mixture of types of goods which are transported together
D19	Unidentifiable goods: goods which for any reason cannot be identified and therefore cannot be assigned to groups 01-16
D20	Other goods n.e.c.

These data show that inland navigation continues to ensure the supply of raw materials for the manufacturing industry and plays an important role in container transport to and from the northwestern European seaports. In the greater Rhine area, inland waterway transport is thus an indispensable part of the logistics chain.

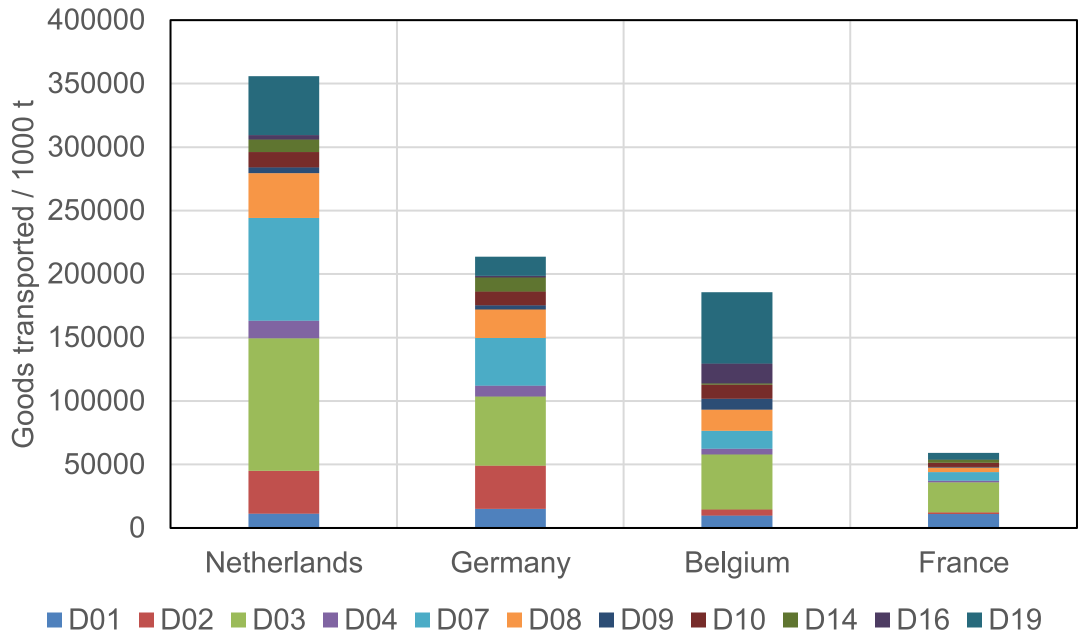

Fig. 2.4: Goods transported in the riparian states of the Rhine in 2016 excluding Switzerland [Dat15]

In contrast to freight transportation, only very little statistical information is available about passenger transportation which is mostly for tourist purposes like river cruises or short distance transportation on ferries.

2.3 Emissions

Figure 1.5 shows how the global carbon dioxide (CO_2) emissions are distributed to various sectors.

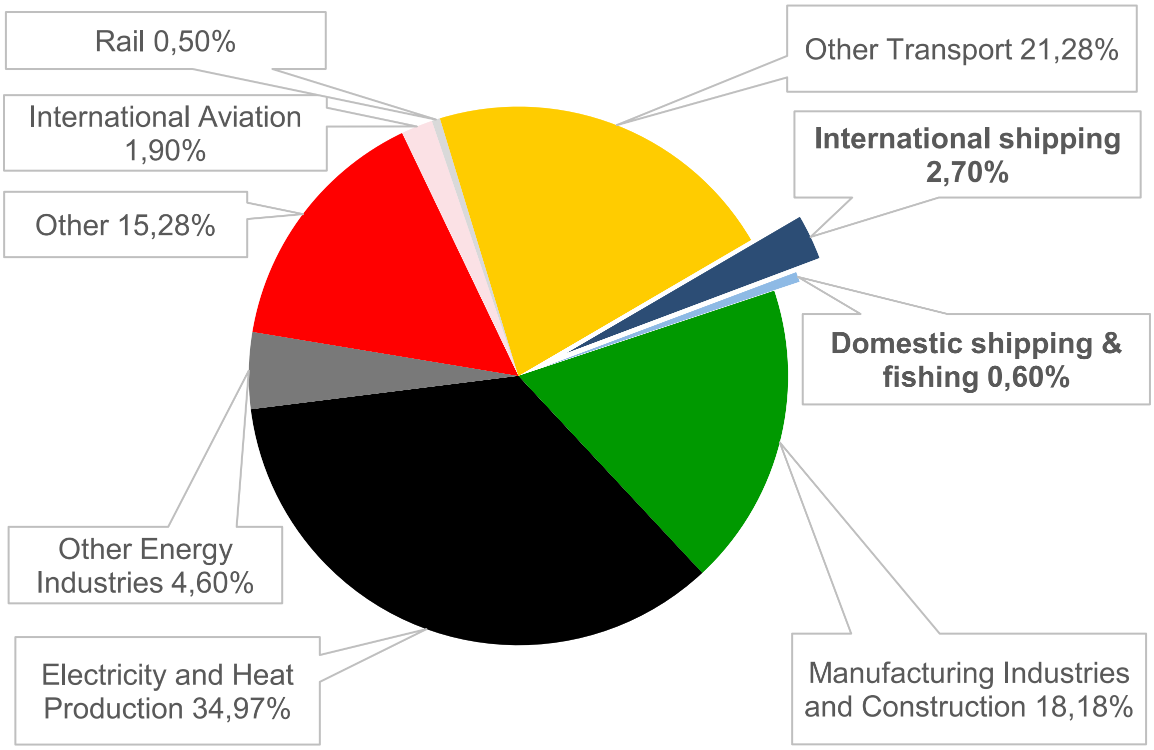

Fig. 2.5: CO_2 emissions of shipping compared to global emissions [Gue11]

With a share of less than 1 % the CO_2 impact of domestic shipping seems negligible on the first view. Nevertheless, it is consented that all sectors will have to bring their contribution to reach the ambitious CO_2 goals in Europe. The development trends show that especially the transportation sector could not realize a remarkable CO_2 reduction because energy efficient technologies could not cover the growth of this sector.

This awareness led to the introduction of CO_2 fleet targets for light duty vehicles and similar regulations are expected for onroad transportation and mobile machinery. Even if there is no intense discussion on CO_2 limitation in the IWT sector yet, the awareness will rise within the next years.

Beside the ongoing discussions on propulsion efficiency and CO_2 emissions, the harmful exhaust components (mainly NO_x, particulates, CO, HC) are limited for ships similar to all other applications in the transport sector. The development of the past emission limit values and an expected regulatory development are shown in Fig. 2.6 for combustion engine propulsion systems with an engine power of more than 130 kW exemplary. A significant reduction of NO_X and particulate emissions had to be realized in the past years. Based on the current changes in legislation in the transportation sector and the former developments a very likely forecast for further emission legislation was created.

This development trend in emission legislation and the upcoming discussions on CO_2 emissions for all transportation applications lead to the necessity of new technologies in IWT.

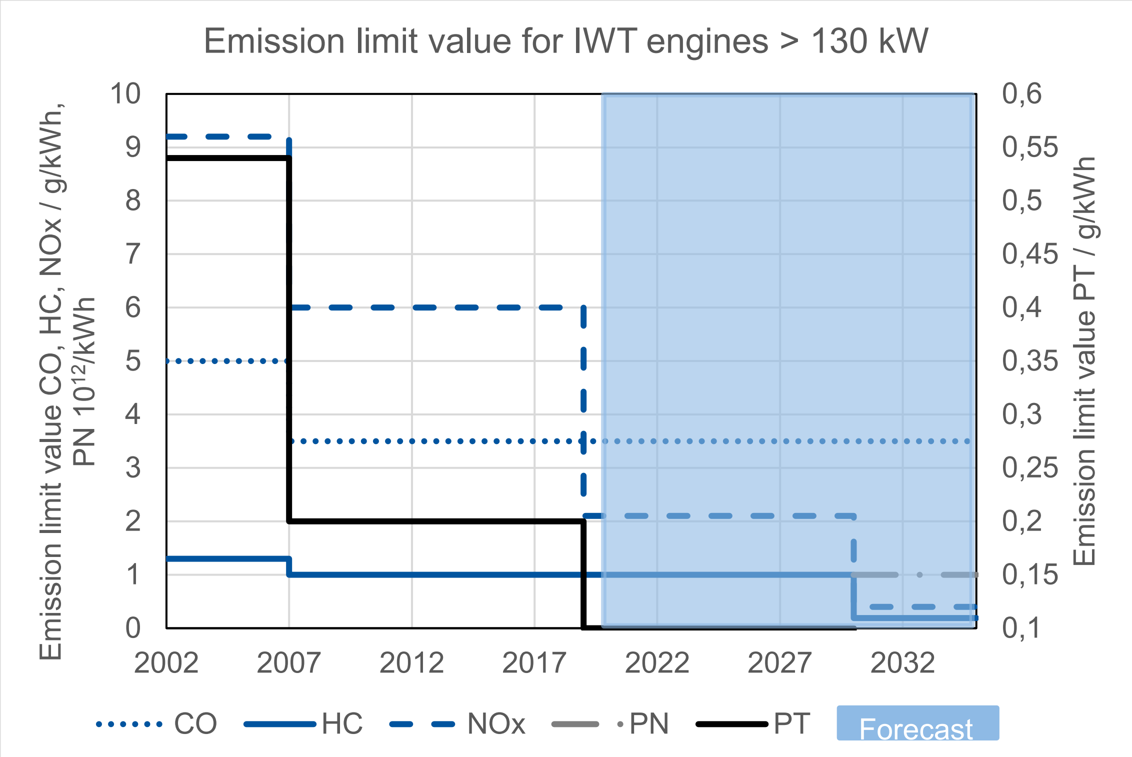

Fig. 2.6: Emission limit value for IWT engines > 130kW [CCN18][EPC98][EPC04][Die18]

2.4 The European inland waterway fleet

The European inland waterway fleet comprises a total of more than 17,000 vessels. In Table 2.2 the number of inland cargo vessels in 2010 is allocated to the respective countries (cf. [Eur18]). The determination of the number of vessels is partly difficult, as statistical data [Dat15] are not complete. The shown data represent a summary and comparison of different institutions. These include the CCNR, Danube Commission, IVR and the respective national authorities. Similar figures are given in [Hek17] for 2012. Cabin ships and other vessels (e. g. public authority vessels) are not included in this list. The number of river cruise ships with more than 40 cabins for the EU including Russia and Ukraine is 459 in 2016 (cf. [Had16]). Moreover, along rivers often ferries can be found in places lacking bridges. For instance, there are more than 20 car ferries on the German section of the Rhine.

Table 2.2: European inland waterway fleet [Eur18]

Country	Dry cargo vessels	Tanker vessels	Push boats	Tug-boats	Cargo-boats	Tank barges	Total
Belgium	806	216	94	10	230	8	1364
Germany	916	419	285	140	789	44	2593
France	860	44	93	0	383	47	1427
Luxembourg	8	16	11	0	0	2	37
Netherlands	3993	1240	649	479	1135	51	7547
Switzerland	17	55	0	2	4	3	81
Rhine countries	**6600**	**1990**	**1132**	**631**	**2541**	**155**	**13049**
Bulgaria	26	4	38	13	161	5	247
Croatia	8	5	10	32	98	21	174
Hungary	78	2	26	53	300	4	463
Moldova	8	5	1	10	26	0	50
Austria	6	5	10	0	54	15	90
Poland	109	2	-	-	431	0	542
Romania	75	4	183	69	984	97	1412
Serbia	62	5	40	82	345	37	571
Slovakia	26	4	41	1	119	32	223
Czech Republic	44	0	-	-	145	0	189
Ukraine	44	3	73	15	472	22	629
Central and Eastern Europe	**486**	**39**	**422**	**275**	**3135**	**233**	**4590**
Total	**7086**	**2029**	**1554**	**906**	**5676**	**388**	**17639**

The historical development of ship sizes goes hand in hand with the dimensions of natural waterways (water depth and width) and their development and extension in the form of canals and locks. The longevity of the ships means that older smaller ships - in some cases over 100 years old - continue to sail today. In many cases, changes and particularly extensions have been made to these vessels over time. In consequence, there is a very heterogeneous inland waterway fleet, whose dimensions nowadays commonly follow the uniform classification of European waterways.

The European inland waterways can be classified according to seven classes defined by the European Conference of Ministers of Transport (ECMT) with several subclasses as described in Table 2.3 and illustrated in Fig. 2.7.

Table 2.3: Classification of European inland waterways [UNC18]

Waterway type	Waterway class	Designation		Motor vessels and barges -type of vessel: gerneral characteristics				Pushed convoys - type of convoy: gerneral characteristics					Min. height under bridges	Symbol on map
				Max. length L (m)	Max. beam B (m)	Draught d (m)	Tonnage T (t)		Length L (m)	Beam B (m)	Draught d (m)	Tonnage T (t)	H (m)	
of regional importance	west of Elbe	I	Barge	38.50	5.05	1.80-2.20	250-400						4.00	
		II	Kampine	50-55	6.60	2.50	400-650						4.00-5.00	
		III	Gustav Koenigs	67-80	8.20	2.50	650-1000						4.00-5.00	
	east of Elbe	I	Gross Finow	41	4.70	1.40	180						3.00	
		II	Type BM-500	57	7.50-9.00	1.60	500-630						3.00	
		III		67-70	8.20-9.00	1.60-2.00	470-700		118-132	8.20-9.00	1.60-2.00	1000-1200	4.00	
of international importance	IV	Johann Welker		80-85	9.50	2.50	1000-1500		85	9.50	2.50-2.80	1250-1450	5.25/7.00	
	V a	Large Rhine vessels		95-110	11.40	2.50-2.80	1500-3000		95-110	11.40	2.50-4.50	1600-3000	5.25/7.00/9.10	
	V b								172-185	11.40	2.50-4.50	3200-6000		
	VI a								95-110	22.80	2.50-4.50	3200-6000	7.00/9.10	
	VI b				140.00	15.00			185-195	22.80	2.50-4.50	6400-12000	7.00/9.10	
	VI c								270-280	22.80	2.50-4.50	9600-18000	9.10	
									195-200	33.00-34.20				
	VII								285	33.00-34.20	2.50-4.50	14500-27000	9.10	

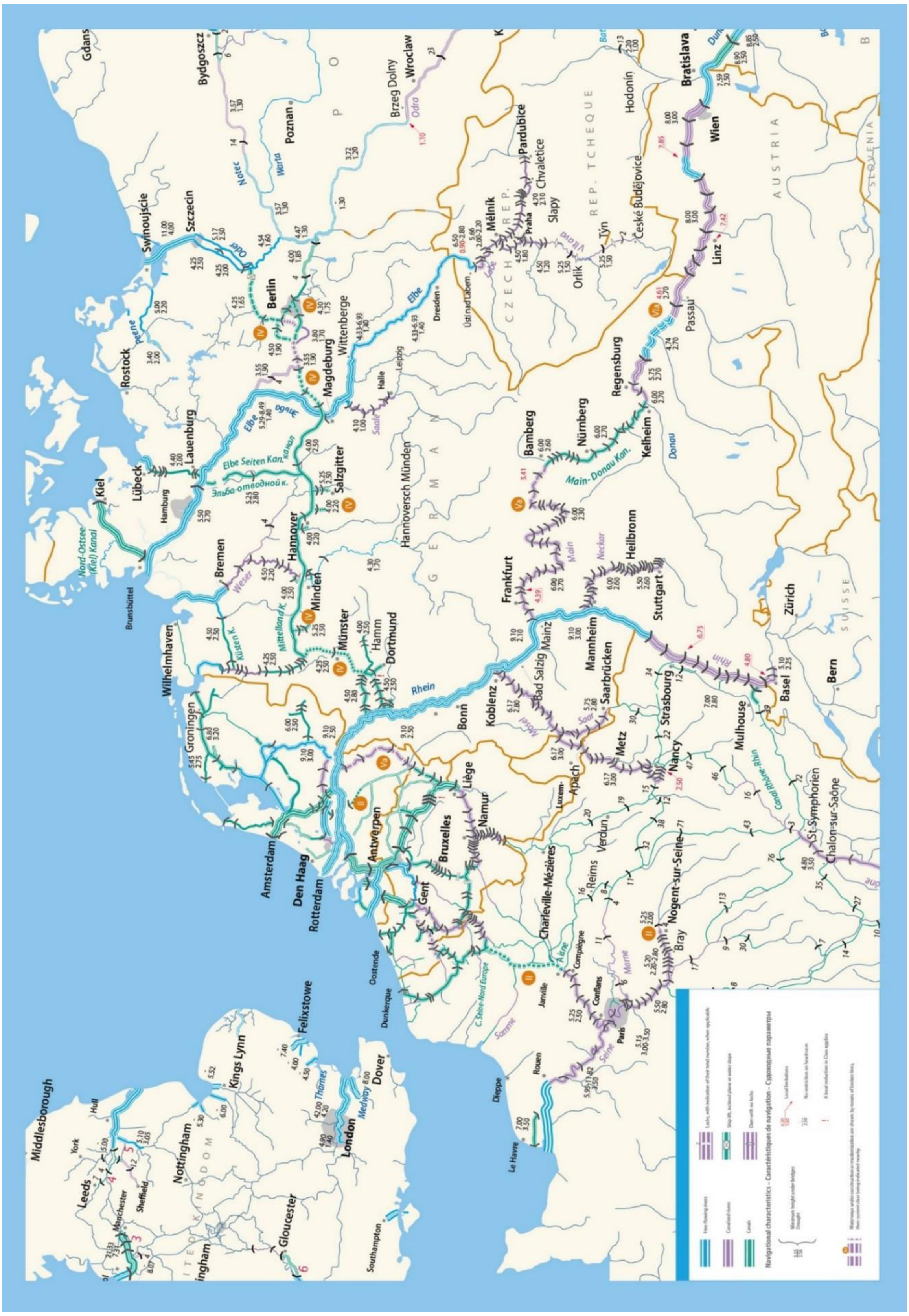

Fig. 2.7: Illustration of classification of inland waterways [UNC18]

In order to achieve the best possible portrayal of the inland waterway fleet, the following types of vessels will therefore be used, which differ in size as well as their operational profile. Nevertheless, the selection considers the most common types and sizes of ships for various application cases. These are a cargo vessel that can navigate on the all navigable German rivers and canals, a pushed convoy as it is common especially on the Lower Rhine, a cabin vessel that runs on bigger German rivers and river ferry which can be found in many places. Based on these types of vessels, the application of hydrogen is investigated in this project. However, it should always be kept in mind that a theoretical transformation to hydrogen propulsion requires many individual solutions for different ship sizes. A good compilation of the different types of inland waterway vessels with data on dimensions and motorization can be found in [Ste16].

2.4.1 Cargo vessel

In Fig. 2.8 a representative example of a cargo motor vessel is depicted. Its main dimensions, propulsive power and operating profile are specified in Table 2.4.

Fig. 2.8: Example of a cargo motor vessel

Table 2.4: Dimensions and operating profile of a cargo motor vessel

Cargo Vessel		
Dimensions	Length	110 m
	Width	11.45 m
	Max. draught	3.65
	Cargo capacity	3285 t
	Container capacity	192 TEU
Propulsive power	Main engine	1300 kW
	Bow thruster	500 kW

The required propulsion power strongly depends on the area of operation. On the Rhine, the maximum propulsion power is selected in such way that the ship can navigate the difficult route between Bingen and St. Goarshausen without external help. This route is characterized by its narrow, curvy profile resulting in high currents. For tributary streams as well as canals the necessary power is lower than for the Rhine. Self-evidently the power for running upstream is higher than that for running downstream. Additionally, the power requirement depends greatly on the driven speed.

In Fig. 2.9 an exemplary load profile is presented for a cargo motor vessel first moving upstream on a large river and then traveling upstream into a tributary stream. The phases of zero power represent the locking processes. This particular ship is equipped with relatively little maximum power of 1100 kW and because of a good order situation was operated at high speed during the measurements. It should be noted that the load profile can look completely different depending on the specific situation. Influencing factors are the travel area, the weather, the order situation, etc. Nevertheless, the exemplary profile represents a good mix and realistic relationships of the various operating conditions.

Using data on natural discharge conditions and water levels in relation to the seasons and simulation of shipping under each condition, the correlation between energy demand and duration of voyages can be determined. Fig. 2.10 show this correlation for the upstream and downstream voyage, respectively.

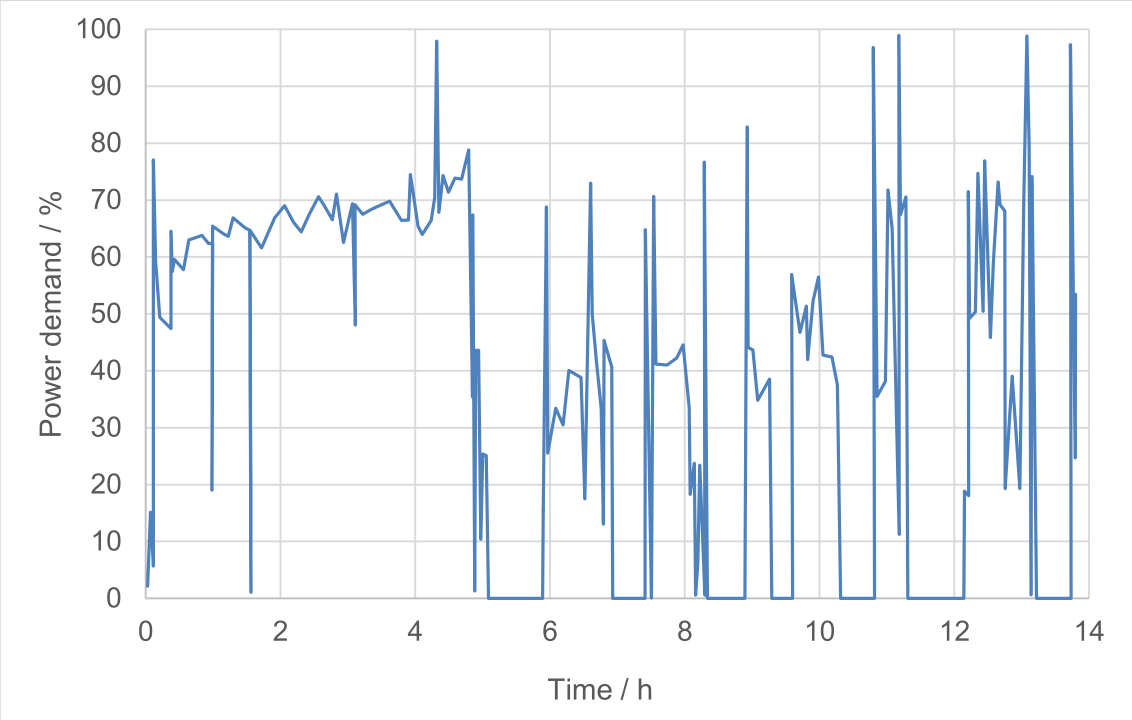

Fig. 2.9: Example operating profile of a day

Regulatory standards define short stopping distances between 305 m and 350 m and a safe operation at unusually rare strong currents at few locations on the Rhine hence leading to a high maximum power demand. During normal operation only a small fraction of this power is used. Recent investigations reveal that in most cases the average engine power is between 30 % and 35 % of the maximum power. The upstream voyage typically takes twice as long as the downstream voyage. At the same time the average engine power during the downstream voyage is typically 1.5 to 2 times lower than with the upstream voyage. [Fri18] Combining this information leads to an engine power between 34 % and 42 % of the maximum power while sailing upstream and between 18 % and 26 % downstream. For the exemplary calculation later in this study the busy route between Antwerp and Mainz is chosen with a total length of 542 km. Based on all these data, an average power of 500 kW seems reasonable for the 50 h upstream voyage, whereas the average power for the 28 h downstream voyage is assumed to be 240 kW.

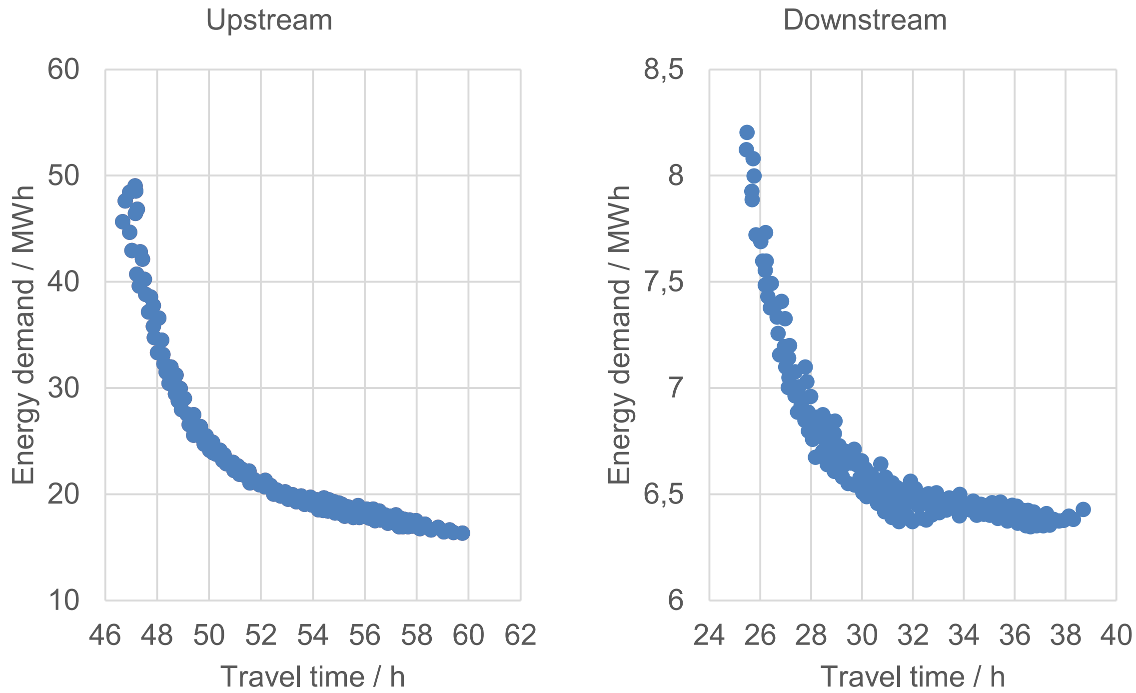

Fig. 2.10: Energy demand of a cargo ship in upstream (left) and downstream (right) voyage

2.4.2 Pushed convoy

Due to their high transport capacity, pushed convoys are well suited for the transport of large quantities of bulk material and so are widely used. As a typical representative for this type of vessels a configuration of six Europa II barges is identified. Two formations are possible: One is to couple three barges side by side and two in front of each other (2x3), as shown in Fig. 2.11. Alternatively, two barges can be coupled side by side and three in front of each other (3x2). As a matter of fact these two formations differ in length and width as specified in Table 2.5.

Fig. 2.11: Example of a pushed convoy

Table 2.5: Dimensions and operating profile of a pushed convoy

	Pushed convoy	
Dimensions	Length	193 m
		268.5 m
	Width	34.2 m
		22.8 m
	Max. draught	Push boat: 1.7 m
		Barges: 2.8 m
	Cargo capacity	16,000 t
Propulsive power	Main engine	3 x 1360 kW
	Bow thruster	2 x 400 kW

A typical route is the connection from Rotterdam to Duisburg and back. Coal and ore transports are carried out upstream in 3x2 or 2x2 arrangement. On the way back, the barges are usually empty and it is driven in 2x3 or 2x2 arrangement. Fig. 2.12 shows the power distribution driving upstream and downstream. Similar results were achieved in the EU project MoVe-IT! [God13]. This reveals an average power consumption of 3000 kW upstream and 1140 kW downstream, resulting in an energy consumption of 93 MWh per cycle of 26 h upstream and 13 h downstream travel. However, this only includes the power requirement for driving and not that for maneuvering and other consumers which can be neglected in this context.

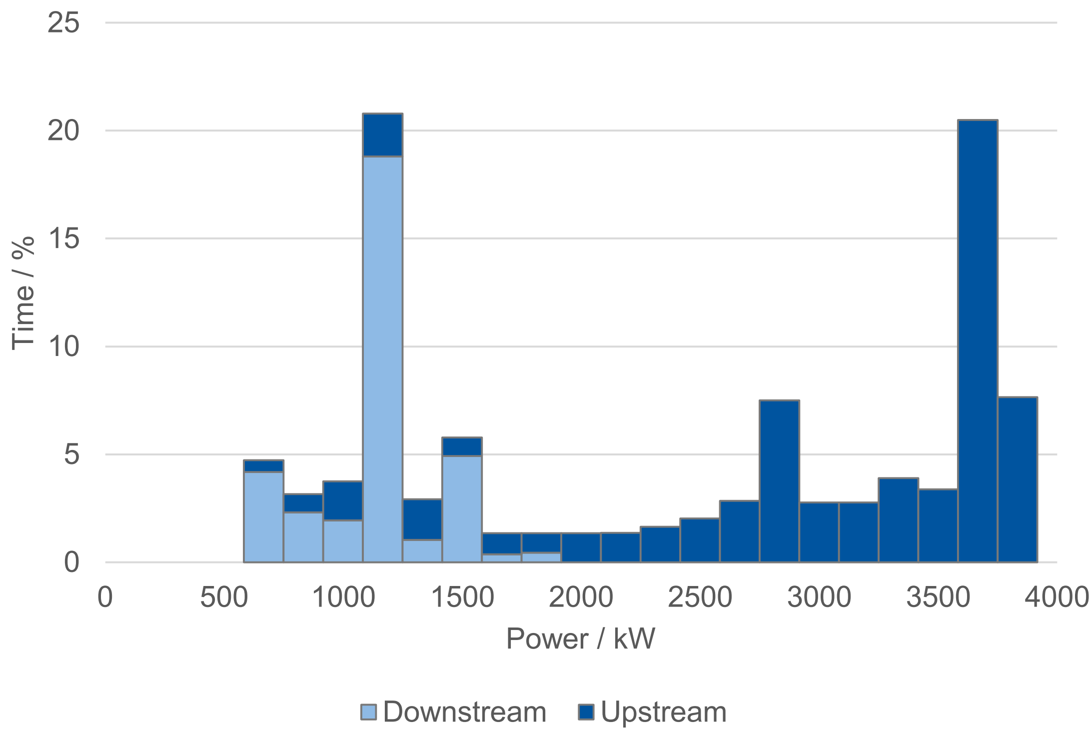

Fig. 2.12: Power distribution of a pushed convoy

Similar to a cargo motor vessel, the operating profile depends on the environmental conditions. In case of high water levels and strong current conditions, it is possible that the vessel is operating at full load for the entire upstream trip 26 h, whereas it needs considerably less power for the same trip under different conditions. The temporal distribution of upstream voyage, downstream voyage and maneuvering in the harbor (preparation and coupling of the barges) is estimated to be about 60 %, 30 % and 10 %, respectively.

2.4.3 Cabin vessel

In Fig. 2.13 a photograph of a typical cabin ship is shown with the corresponding details regarding dimensions and propulsion system given in Table 2.6. These vessels are usually equipped with a diesel-electric propulsion system. This means that a diesel engine and a generator (genset) produce electricity which is afterwards converted to propulsive power in an electric motor. Additionally, the hotel operation consumes a significant amount of electrical energy.

Fig. 2.13: Example of a cabin vessel

The considered vessel is equipped with two large gensets of roughly 1 MW each. Simplifying, it can be assumed that both large gensets are used during sailing. When the ship is in port, one genset is required for hotel operation. Additionally, two smaller gensets are kept available for emergency maneuvers. For propulsion four 300 kW electric motors are installed as well as two pumpjets of 340 kW each. The load conditions are strongly dependent on the timetable. If two destinations are far apart from each other, the vessel operates at full load. If they are close together, the ship operation is more efficient. Shore power is currently only available at few destinations and thus is of little importance. Data on the temporal distribution of the power requirements are available at the shipping companies, but unfortunately not publicly accessible.

Table 2.6: Dimensions and operating profile of a cabin vessel

	Cabin Vessel	
Dimensions	Length	135 m
	Width	11.45 m
	Max. draught	2 m
	Passengers	190
	Crew	45
Propulsive power	Diesel electric engine	
	Gensets	2x994 kW
		2x383 kW
	Propulsion	4x300 kW
	Pumpjets	2x340 kW

2.4.4 Rhine ferry

The photograph of a typical Rhine car ferry is depicted in Fig. 2.14 with the corresponding characteristics given in Table 2.7. It is characterized by short turnaround times that split up in of pure travel times and waiting times for loading and unloading.

However, the power requirement is determined by the regulatory situation and customer requirements. As a rule, for maintenance work, the ferries should be able to sail to the shipyard without external help. For example, this could require operating at full load for half a day.

Fig. 2.14: Example of a Rhine ferry

Table 2.7: Dimensions and operating profile of a Rhine ferry

Rhine ferry		
Dimensions	Length	35 m
	Width	10 m
	Max. draught	1.0 m
	Cargo capacity	60 t
Propulsive power	Main engine	300 kW

These ferries usually operate between 12 and 15 hours per day. The duration of one roundtrip is in the range of six minutes. These days, customers tend not to accept long waiting times any more so that many ferries constantly travel back and forth, as long as customers are present on either side of the river. During the short waiting times ferries are not moored, but keep their position by pushing against the dock by the help of engine thrust. This leads to a steady average shaft power demand of roughly two thirds of the maximum engine power. This information is an averaged result of own inquiries.

3 Hydrogen Applications: Current Status

In this chapter, the current status of hydrogen applications is presented beginning with hydrogen projects in the shipping sector in section 3.1. This is followed by a description of the developments in other sectors the technologies might be transferred from in section 3.2. Finally, in section 3.3 the chemical properties of hydrogen are presented pointing out the advantages and challenges of hydrogen use.

3.1 Hydrogen applications in the shipping sector

An overview of past and current hydrogen projects in the field of shipping is given in Table 3.1. So far, the projects focused on niche applications whose most prominent examples are pointed out in the following. The Alsterwasser was the first fuel cell ship operating as a tourist boat on the canals of Hamburg and has transported already 50,000 passengers. The submarine class U212A is equipped with a fuel cell for electricity generation while diving and designed to be extremely quiet. The most powerful application that has not been constructed, but only exists as a study, is the SF Breeze, a hydrogen fuel cell powered high-speed passenger ferry for the San Francisco Bay Area with a maximum power of 2.5 MW. All three applications use or are designed to use the Proton Exchange Membrane (PEM) fuel cell (FC) technology [Tro17].

Table 3.1: Overview of hydrogen in shipping projects [Tro17]

Project	Concept	Main partners	Year	Fuel Cell	Capacity
E4Ships Toplaterne	Supporf of IGF Code development to include a FC chapter and set the regulatory baseline for the use of maritime FC systems	DNV GL., Meyer Werft, Thyssen Krupp Marine Systems, Lürssen Werft, Flensburger Schiffbaugesellschaft VSM	Phase1: 2009 - 2017 Phase2: 2017 - 2022	-	-
RiverCell Elektra	Feasibility study for a fuel cell as part of a hybrid power supply for a towboat	TU Berlin, BEHALA, DNVGL,	2015 - 2016	HTPEM	-
ZemShip Alsterwasser	100kW PEMFC system developed and tested onboard of a small passenger ship in the area of Alster (Hamburg, Germany)	Proton Motors, GL, Alster Touristik GmbH, Linde Group	2006 - 2013	PEM	96kW

FCSHIP	Assess the potential for maritime use of FC and develops a Roadmap for future R&D on FC application on ships	DNV GL., LR, RINA, EU GROWTH program	2002 – 2004	MCFC, SOFC, PEM	-
New-H-Ship	Research project on the use of hydrogen in marine applications	INE (Icelandic New Energy), GL, DNV, etc	2004 - 2006	-	-
Nemo H2	Small passenger ship in the canals of Amsterdam	Rederij Lovers, etc.	2012 - present	PEM	60 kW
Hornblower Hybrid	Hybrid ferry with diesel generator, batteries, PV, wind and fuel cell	Hornblower	2012 - present	PEM	32 kW
Hydro-genesis	Small passenger ship which operates in Bristol	Bristol Boat Trips, etc.	2012 - present	PEM	12 kW
MF Vagen	Small passenger ship in the harbor of Bergen	CMR Prototech, ARENA-Project	2010	HTPEM	12 kW
Class 212A/214 Submarines	Hybrid propulsion using a fuel cell and a diesel engine	CMR Prototech, ARENA-Project, Thyssen Krupp Marine Systems, Siemens	2003 - present	PEM	306 kW,
SF-BREEZE	Feasibility study of a high-speed hydrogen fuel cell passenger ferry and hydrogen refueling station in San Francisco bay area	Sandia National Lab., Red and White Fleet	2015 - present	PEM	120 kW per module total power 2.5 MW
FELICITAS	PEFC-Cluster-improving PEFC reliability and power level by clustering	NuCellSys, PhG IVI, CCM	2005 - 2008	PEM	Cluster System
Cobalt 233 Zet	Sport boat employing hybrid propulsion system using batteries for peak power	Zebotec, Brunnert-Grimm	2007 - present	PEM	50 kW

3.2 Possibilities of technology transfer

In the field of forklifts and similar industrial trucks, in Germany solutions with electric motors and fuel cell drives are already market-available from a number of manufacturers and are tested in practice [HMU13]. In the city of Basel in Switzerland, a sweeper with fuel cell drive was tested in a field trial. In addition to a significant reduction in energy consumption, however, problems with practical suitability were also identified [Emp18]. The prerequisite for operating hydrogen powered vehicles is the availability of hydrogen as fuel, for example in the form of gas stations on the company premises. With increasing numbers of produced units and the consistent suitability for practical use, prices can be expected to drop significantly facilitating a large-scale introduction of these vehicles.

Fuel cell drives have also been developed in the field of local public transportation with buses [FCB17a] and private car transport in recent years. Meanwhile, serial production fuel cell drive passenger cars are available on the European marked and further models have been announced for the next years from leading car manufactures. In France the first FC e-bike was introduced in 2018 [Huc18]. In Germany, the National Innovation Program Hydrogen and Fuel Cell Technology (NIP) [NIP18] promotes development in all modes of transport. In 2017 Alstom introduced a fuel cell powered regional train [Als18] that has entered commercial operation in September 2018. In February 2018 also Siemens announced to develop a fuel cell drive for trains in cooperation with RWTH Aachen University [NOW18].

Beside all these smaller initiatives, the first country having established a comprehensive strategy for hydrogen is Japan [BHS18]. This strategy aims for a hydrogen based society by 2050. The key aspects are:

1. Realizing low-cost hydrogen use
2. Developing international hydrogen supply chains
3. Renewable energy expansion in Japan and regional revitalization
4. Hydrogen use in power generation
5. Hydrogen use in mobility
6. Hydrogen use in industrial processes and heat utilization
7. Using fuel cell technologies
8. Using innovative technologies
9. International expansion
10. Promotion of citizens' understanding and regional cooperation

Within the subaspect "Hydrogen use in mobility" Japan aims at 200,000 hydrogen vehicles and a network of 320 independent hydrogen stations by 2025. The hydrogen production shall be renewable-based and a commercialization of the hydrogen stations is to be pushed. The number of FC buses shall be increased to around 100 by 2020 and around 1200 by 2030. In the same time frames, the number of hydrogen powered forklifts shall rise from 500 to 10,000. Moreover, the development and commercialization of FC trucks and the promotion of FCs for ships is included in the strategy.

In a similar timeframe the European institutions like H_2-Mobility aim to initialize up to 400 hydrogen gas stations to enable a significant rise of the fuel cell vehicle share in Europe.

The increasing level of activities in the automotive sector can have a positive impact on the use of the technology in shipping. It can be expected that prices for hydrogen as well as components such as storage tanks and energy conversion technologies will drop with the technology being on the rise. Simultaneously, the number of suppliers, the variety of components, as well as their performance and reliability will increase. The shipping sector can also profit from advancements in the hydrogen infrastructure

Besides making use of similarities with the automotive sector, the shipping industry can profit even more from the experience with hydrogen applications in trains. This is because to a certain extent the boundary conditions in the shipping and railroad sectors are alike. In both cases, a propulsion power of up to several MW is used. The large number of daily operating hours comes along with long design ranges. Furthermore, both ships and trains are constructed for a lifetime of ten thousands of operating hours. Differences can be seen in the power profile which tends to be more dynamic with trains than with ships. This, however, cannot be generalized since it highly depends on the very specific use cases.

3.3 Hydrogen: Chemical properties

This section gives an overview of the occurrence and chemical properties of hydrogen.

With 93% of the existing atoms and 75% of the mass hydrogen is by far the most abundant element in the universe mostly occurring in the atomic state (H) due to environmental conditions. On earth, because of its reactivity, hydrogen only occurs in bound form. However, hydrogen is rarely found in the molecular form (H_2). Instead, it is most common in inorganic hydrides, especially in water (H_2O) and in a variety of organic compounds such as hydrocarbons, e.g. alcohols, aldehydes, acids, fats, carbohydrates or proteins (see [Sic16] and [Eic10]). Due to the low atomic mass, hydrogen accounts for only 0.12% of the earth's mass. Table 3.2 summarizes the most important properties of hydrogen.

With a boiling temperature of -253 °C and a melting temperature of -259.2 °C, hydrogen is an almost permanent gas. Since the critical temperature at -239.96 °C is also extremely low, a pressure increase to support liquefaction (critical pressure 13.1 bar) is only possible to a limited extent.

With the stated ignition and detonation limits (see Table 3.2), hydrogen can ignite in a wide range of concentrations compared to other fuels. In a combustion process, this would allow extremely lean air/hydrogen mixtures (λ ≈ 10) (see [Eic10]). The difference between the ignition and detonation limits lies in the type of combustion. Deflagration refers to a combustion with subsonic velocity, detonation to a combustion with supersonic velocity. The self-ignition temperature of hydrogen is higher than that of other fuels, but the minimum ignition energy is significantly lower.

Hydrogen is a colorless and odorless, non-toxic gas at room temperature. It is extremely light in comparison to air (ρ = 1.29 kg/m³) and volatilizes quickly in air. These are great advantages for hydrogen being used in sensitive ecosystems as many waterways are.

Hydrogen evaporates easily and diffuses through a variety of materials due to the small molecule size. This makes the storage and transport of hydrogen quite complex. To cope with this, special steels or diffusion barrier layers have to be used (cf. [She17]). Furthermore, embrittlement of materials in contact with hydrogen is a significant problem. However, the rapid volatilization in air can also be positive from a safety point of view.

Table 3.2: Properties of hydrogen [Eic10]

Symbol	H
Relative atomic mass	1.008
Molar mass	2.016 kg/mol
Diffusion coefficient in air (0 °C, 1,013 bar)	0.61 cm^2/s
Boiling temperature	-252.9 °C
Melting temperature	-259.2 °C
Critical temperature	-239.96 °C
Mass density, gaseous (0 °C, 1.013 bar)	0.09 kg/m^3
Mass density, liquid (-252.9 °C, 1.013 bar)	70.8 kg/m^3
Mass density, solid (-259.2 °C, 1.013 bar)	76.3 kg/m^3
Volumetric calorific value	0.01 MJ/dm^3
Gravimetric calorific value	119.97 MJ/kg
Lower explosion limit (ignition limit)	4 Vol%H_2 (λ = 10.1)
Lower detonation limit	18 Vol%H_2 (λ = 1.9)
Stoichiometric mixture	29.6 Vol%H_2 (λ = 1)
Upper explosion limit	58.9 Vol%H_2 (λ = 0.29)
Upper detonation limit (ignition limit)	75.6 Vol%H_2 (λ = 0.13)
Ignition temperature	585 °C
Minimum ignition energy	0.017 mJ

The chemical properties of hydrogen reveal a very low volumetric energy density, but a very high gravimetric energy density. The technical challenge is therefore to increase the former. Several possibilities for this are discussed in section 4. The comparison of the net calorific values of some fuels is shown in Fig. 4.15. The given values are based on publications [Bou11], [Bas16], [Höh03] and [Sta18]. A similar presentation is available in [She17]. The values vary slightly in the literature, as the reference temperatures differ and the composition of natural gas and fuels is different.

Hydrogen is a highly flammable gas which, due to its properties, is excellently suited as a fuel. The handling requires great care and compliance with the safety regulations. However, the necessary safety regulations, if not yet existent, need not differ significantly compared to other fuels as the hazards are very similar. Necessary training measures for the handling of hydrogen are discussed in section 6.

Although CO_2 is not emitted directly when hydrogen is converted to other forms of energy, the global warming potential related to emissions in the various ways of hydrogen production must not be ignored. It is discussed in section 4.1.

4 Technological Feasibility

In the following section the relevant technological aspects regarding the use of Hydrogen as a fuel in IWT are discussed. I order to give a holistic overview the whole chain from production to conversion will be considered in four steps. On this basis, in chapter 4.5, the most promising technologies for the four exemplary ships defined in chapter 2.4 will be assessed.

4.1 Infrastructure and supply

In a first step, the various sources of hydrogen will be discussed with regard to their technology and their impact on ecology and economy. Furthermore, the local distribution of the most important hydrogen sources will be discussed. In a final step, the possible development potential of the future hydrogen infrastructure is estimated.

4.1.1 Methods of hydrogen production

Hydrogen production can be differentiated into reforming from fossil fuel and production from electrolysis of water as described subsequently.

4.1.1.1 Reforming of fossil fuels

The following sections briefly summarize the ways in which hydrocarbons are reformed. Due to the limited fossil fuels (hydrocarbons) and the carbon dioxide produced as a by-product in all the processes described below, reforming must be assessed critically.

<u>Steam reforming</u>

Steam reforming is an endothermic catalytic reaction of light hydrocarbons with water vapor (cf. [Eic10]). Production is possible in large-scale industrial plants at pressures between 20 bar and 40 bar and temperatures between 700 °C and 900 °C. The net reaction equation is given in following equation (4.1).

$$C_nH_mO_k + (n-k)H_2O \rightarrow nCO + \left(n + \frac{m}{2} - k\right)H_2 \qquad (4.1)$$

The simplest form of this reforming is carried out with natural gas (consisting primarily of methane, CH_4). The following reactions occur (cf. [Eic10]):

$$CH_4 + H_2O \rightarrow CO + 3H_2;\ \Delta_R H = 206\frac{kJ}{mol} \qquad (4.2)$$

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2;\ \Delta_R H = \ 165\frac{kJ}{mol} \tag{4.3}$$

The resulting synthesis gas – a mixture of carbon monoxide and hydrogen with proportions of carbon dioxide, water vapor and residual hydrocarbons – is a widely used source product in the chemical industry. In addition to ammonia synthesis, methanol production and Fischer-Tropsch synthesis, it is also used to produce hydrogen. With the water gas reaction (shift reaction) the gas cooled down to about 400 °C is further processed in a slightly exothermic catalytic reaction with water vapor:

$$CO + H_2O \rightarrow CO_2 + H_2;\ \Delta_\mathrm{R} H = \ -41\frac{kJ}{mol} \tag{4.4}$$

After the carbon dioxide has been separated, hydrogen with a purity of about 99.99 % is produced. The production capacities of steam reforming plants range from 150 Nm³/h to 100,000 Nm³/h hydrogen with efficiencies of 75 % to 80 %.

Partial oxidation

Partial oxidation is suitable for reforming heavy hydrocarbons with the help of oxygen. The catalytic reaction takes place exothermically with the following net reaction equation (cf. [Eic10]):

$$C_nH_m + \left(\frac{n}{2}\right)O_2 \rightarrow nCO + \left(\frac{m}{2}\right)H_2 \tag{4.5}$$

The reaction takes place at temperatures between 600 °C and 850 °C using catalysts. Otherwise, temperatures between 1250 °C and 1400 °C are necessary (see [Zak10]). The resulting synthesis gas can be converted into hydrogen and carbon dioxide analogous to equation (4.4). This process achieves capacities of 100,000 Nm³/h with an efficiency of about 70 %. The exothermic reaction does not require an external heat source but the supply of oxygen. Overall, the partial oxidation is therefore less efficient than the steam reforming, but allows a wide range of hydrocarbons to be converted without the use of methane (see [Eic10]).

Autothermal reforming

Autothermal reforming is a combination of steam reforming and partial oxidation profiting from the advantages of both ways of reforming. The net reaction equation for methane is as follows (cf. [Eic10]):

$$4CH_4 + O_2 + 2H_2O \rightarrow 4CO + 10H_2;\ \Delta_R H = 170\frac{kJ}{mol} \tag{4.6}$$

The catalytic reaction is slightly endothermic and takes place at temperatures of 850 °C. The advantages of the process are the independence of an external heat supply, but oxygen must be provided and the exhaust gases must be cleaned in a more complex process due to formation of nitrogen oxides (NO_x) (see [She17]).

4.1.1.2 Electrolysis of water

Electrolysis is the conversion of electrical energy into chemical energy. In the considered case it means the decomposition of water molecules (H_2O) into hydrogen (H_2) and oxygen (O_2) by applying direct current.

$$2H_2O(l) \xrightarrow[Electrolysis]{} 2H_2(g) + O_2(g);\ \Delta_R H = 572\frac{kJ}{mol} \tag{4.7}$$

As an electrolyte, pure water dissociates to a small extent into H^+ ions and OH^- ions and is already conductive in this state (cf. [Eic10]). However, the instability of the H^+-ion leads to a fast connection with a water molecule, so that the so-called oxonium ions H_3O^+ and hydroxide OH^- ions are formed.

$$H_2O(l) \rightleftarrows H^+(aq) + OH^-(aq) \tag{4.8}$$

$$2H_2O(l) \rightleftarrows H_3O^+(aq) + OH^-(aq) \tag{4.9}$$

From a chemical point of view, the electrolysis of water is a redox reaction, a combination of oxidation (electron release) and reduction (electron absorption). At the cathode, the minus pole of the electrolysis, electron absorption takes place in addition to the dissociation of the water by reducing the dissociated oxonium ion H_3O^+:

$$\begin{gathered} 8H_2O \rightarrow 4H_3O^+ + 4OH^- \\ 4H_3O^+ + 4e^- \rightarrow 2H_2 + 4H_2O \end{gathered} \tag{4.10}$$

This leads to the net cathode reaction:

$$4H_2O(l) + 4e^- \rightarrow 2H_2(g) + 4OH^-(aq) \tag{4.11}$$

The anode, the positive pole of electrolysis, absorbs electrons from the hydroxide ion, which is oxidized to water under release of oxygen.

$$4OH^-(aq) \rightarrow 2H_2O(l) + O_2(g) + 4e^- \tag{4.12}$$

The shown reactions describe the behavior of alkaline electrolysis (AEL). In practice, potassium hydroxide KOH is often used instead of pure water as electrolyte for increasing the conductivity of the solution. The reactions take place at low temperatures between 60 °C and 80 °C (cf. [Smo10] [She17]). AEL has been in commercial use for about 100 years and this type of plant dominates the market. The gross efficiency ranges between 65 % and 82 %. The largest plants will have a hydrogen production capacity of 760 Nm^3/h with an overall electrical power consumption of 5.3 MW(see [She17]).

Another process of electrolysis that has been commercially used in smaller applications for about 20 years is the proton exchange membrane electrolysis (PEMEL). As the name suggests, a proton conducting polymer membrane (PEM) is used as the electrolyte. With 50 °C to 80 °C (cf. [Smo10]), the working temperatures are similar to those of AEL. These kind of plants are usually slightly smaller than AEL plants and can produce up to 240 Nm³/h with a required electrical power of 1.15 MW at a system efficiency between 65 % and 78 % (see [She17] [Smo10]). The net reaction equations at the cathode and anode, respectively, are shown below:

$$4H_3O^+(aq) + 4e^- \rightarrow 2H_2(g) + 4H_2O(l) \tag{4.13}$$

$$6H_2O(l) \rightarrow O_2(g) + 4H_3O^+(aq) + 4e^- \tag{4.14}$$

A newer method of electrolysis is high temperature electrolysis (HTEL) with solid oxides (solid oxide electrolysis, SOEL). The reactions take place at temperatures between 700 °C and 1000 °C (cf. [Smo10]). At present, this electrolysis is still on a laboratory scale, achieving efficiencies of up to 85 % (see [She17]). The net reaction equations at the cathode and anode are shown below:

$$2H_2O(g) + 4e^- \rightarrow 2H_2(g) + 2O^{2-} \tag{4.15}$$

$$2O^{2-} \rightarrow O_2(g) + 4e^- \tag{4.16}$$

4.1.1.3 Other methods

Hydrogen can also be obtained in a variety of other processes as a by-product or directly. It is a byproduct of gasoline reforming, ethene production or chlor-alkali electrolysis, for example. The direct splitting (cracking) of mostly long-chain hydrocarbons can be carried out at high temperatures above 800 °C without the formation of carbon dioxide and follows the following net reaction equation:

$$C_nH_m \rightarrow nC + \left(\frac{m}{2}\right)H_2 \tag{4.17}$$

A further development of this process is the Kværner process, which takes place in a plasma torch at temperatures of around 1600 °C. The high temperatures and the low hydrogen yield compared to steam reforming make this process rather uneconomical. Coal gasification is another process based on the conversion of a carbon carrier with an oxygen-containing gasification agent (see [Eic10]). The common disadvantage of cracking and coal gasification is the use of fossil fuels.

Other approaches use solar radiation to produce hydrogen. Highly concentrated radiation splits water and carbon dioxide into hydrogen, carbon monoxide and oxygen. At temperature ranges of 800 °C to 1500 °C. Redox materials can function as catalysts in this context. Another method using single photons stimulates chemical reactions separating water and carbon dioxide. Additionally using electrical energy can accelerate the reactions which take place at temperatures below 100 °C. These solar processes are being intensively researched at the German Aerospace Center, e.g. [DLR18a] [DLR18b].

The biological production of hydrogen on the basis of bio photolysis, for example by green algae or by fermentation of biomass, are still in the research stage and have so far played little role. However, as they are based on renewable raw materials, they could become more important in the future. Current developments and future research needs for hydrogen from biomass can be found in [FNR06].

4.1.2 Current situation of hydrogen production

Nowadays 96 % of the hydrogen worldwide originate from fossil sources, half of which from natural gas. Coal gasification is a common method of hydrogen production in China. For cost reasons, only 4 % of the hydrogen are produced by means of electrolysis of water which is shown in Fig. 4.1 [APr18].

According to a study in the context of certifHY project, "the global demand for hydrogen in 2010 was around 43 million tons and was foreseen to reach 50 million tons by 2015, primarily as a result of the demand of the ammonia production, methanol and petroleum refinery operations. Asia and Pacific are the world’s leading consumers of hydrogen representing 1/3 of the global consumption followed by North America and Western Europe with a share of 16% (7 million tons H_2). [Fra15]

The CertifHy project came to the conclusion, that in 2015 "the hydrogen production is led by a few large industrial actors who play a key role in establishing internally a market price" [Fra15]. The Shell Study [She17] announces a price of 9.50 € per kg.

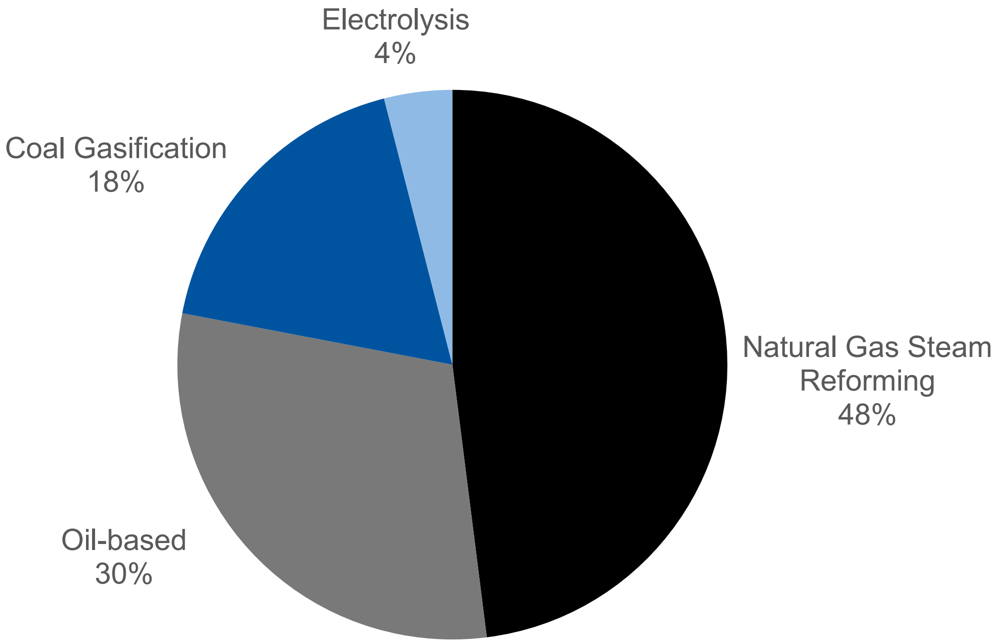

Fig. 4.1: Fraction of hydrogen from different technologies [APr18]

Nowadays, hydrogen is mainly used as a resource in the chemical industry. Because chemical plants need a good transport connection for bulk cargo, they are often located directly next to waterways. This can be seen in Fig. 4.2 showing the major hydrogen production sites in Germany and the Benelux.

One application using electrolysis for hydrogen production is the Power-to-X (P2X) concept. Excess electricity is converted to chemically stored energy for storage and re-conversion or utilization in a different way, as feedstock or fuel, e.g. The variable x can refer to various kinds of chemicals. In Fig. 4.3 the locations of P2X projects in Germany are marked on the map. The projects are evenly scattered across the country [PTG18]. The number of projects accentuates the intensity of research and endeavor of implementation of this kind of technology.

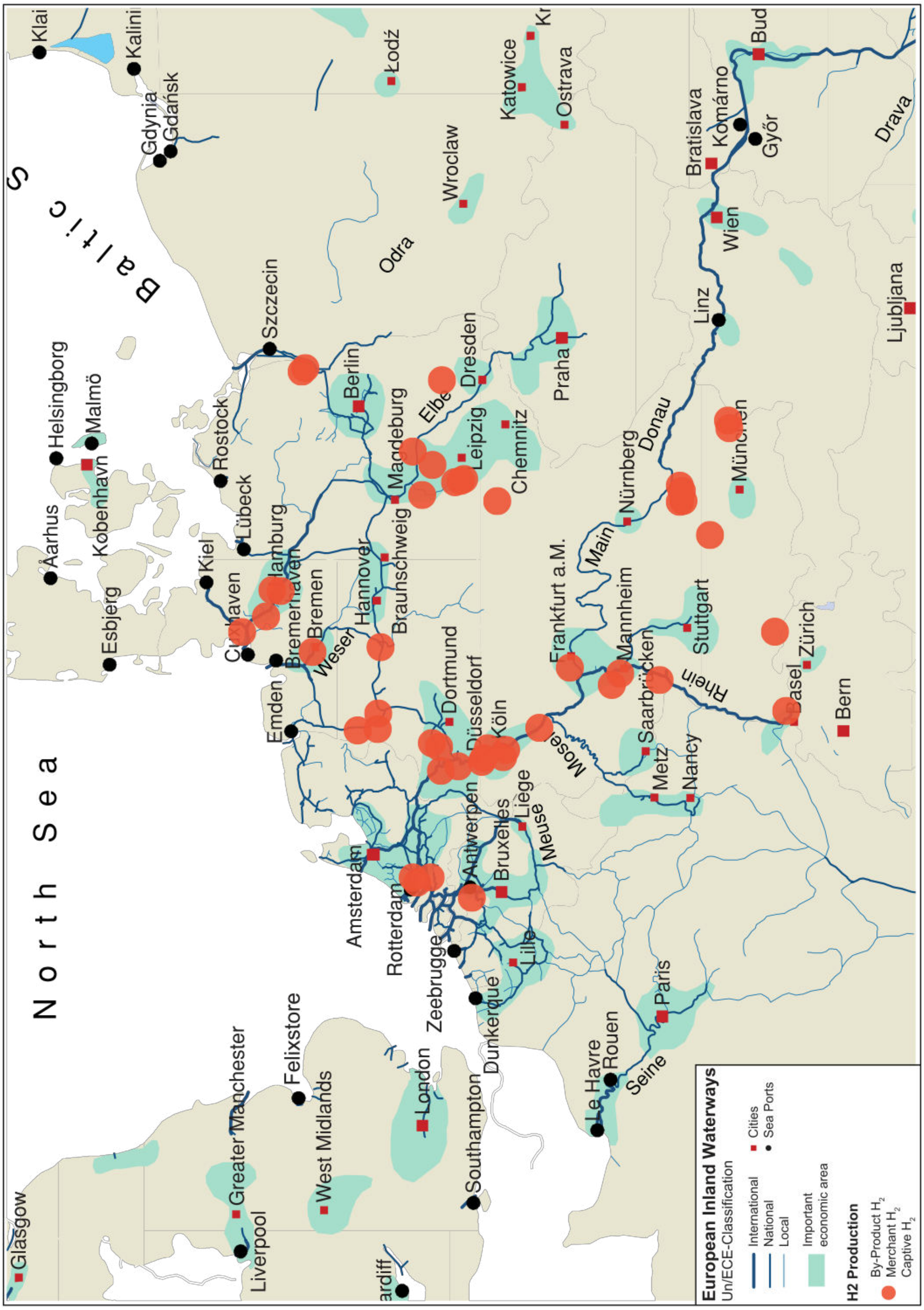

Fig. 4.2: Hydrogen production sites [Fra15]

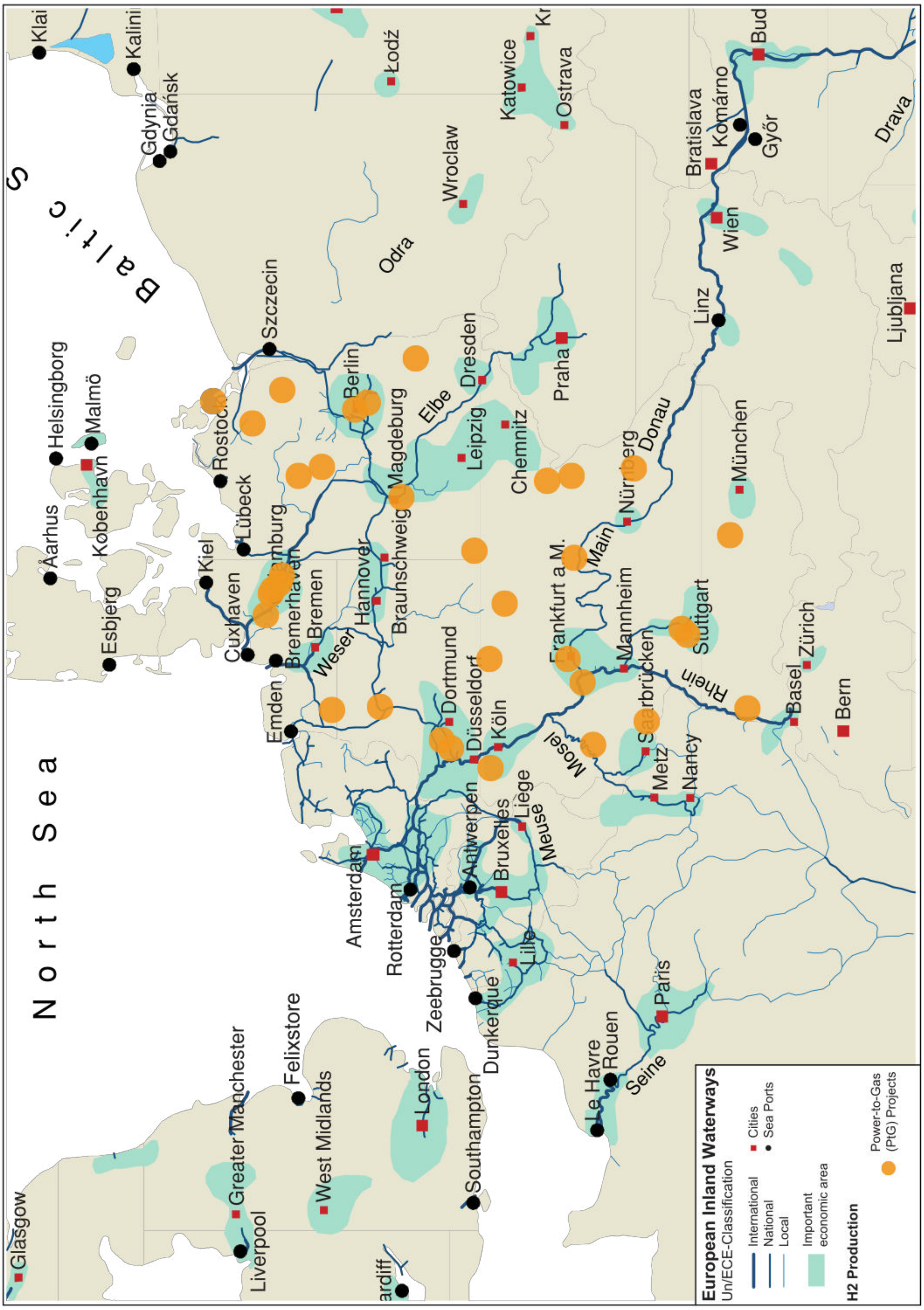

Fig. 4.3: Power-to-X project sites in Germany based on [EPG18]

4.1.3 Ecological and economical assessment

Regarding local emissions, using hydrogen in a combustion process or in fuel cells is attractive, since the reaction product is pure water without any direct greenhouse gas emissions. However, a comprehensive evaluation always requires consideration of the entire process of fuel production, distribution and use. The evaluation of energy efficiency is usually carried out by the well-to-tank (WTT) approach for power generation and the tank-to-wheel (TTW) approach for implementation in the vehicle. Combined, this results in a well-to-wheel (WTW) view of the entire process.

The energy consumption for supplying energy in different forms on different paths as well as the corresponding greenhouse gas emissions are analyzed in a study by the Joint Research Center of the European Commission, Eucar and concawe (JEC) [Edw14]. These data are the basis for the following analyses comparing various paths of providing hydrogen. Similar data are also published in the Shell study [She17].

In Fig. 4.4 the results of the WTT analysis are depicted showing the primary energy consumption on the left and the greenhouse gas emissions on the right axis with the left and the right bar of each pair corresponding to the respective side.

The blue bars correspond to hydrogen production by means of thermal reforming. The calculations are based on pipeline transport of natural gas over a distance of 4000 km and in case of central reformation an additional transport of the hydrogen over 100 km.

It is clearly visible that on-site reformation requires more energy than central reformation due to the higher efficiency of large-scale refineries. Road transport of hydrogen is more inefficient than pipeline transport, but due to the relatively small distance of 100 km the calculations is based on this effect appears to be negligible. The previously described alternatives are about delivering the hydrogen in compressed form. Another way exemplarily compared here is central reformation and subsequent liquefaction in order to increase the volumetric power density for road transport, followed by vaporization and compression on site. Do to the high energy consumption of both the liquefaction and the compression, this path even exceeds the on-site reformation. It only pays off for long distance, e.g. intercontinental, hydrogen transport, because any extra conversion reduces efficiency. That is, hydrogen should be produced in the form it is stored onboard the vessel. These deliberations refer to the primary energy consumption, but also hold true for CO_2 emissions.

Additionally, the impact of hydrogen production via electrolysis is considered. In a first option, the natural gas is used to run a combined cycle gas turbine (CCGT), a highly efficient process creating electricity. This electricity is then used for on-site water electrolysis. The energy effort is three times as great compared to the most efficient way of directly reforming the natural gas. Hence, if natural gas is the envisaged source for hydrogen the detour via electricity is not beneficial from an energetic point of view.

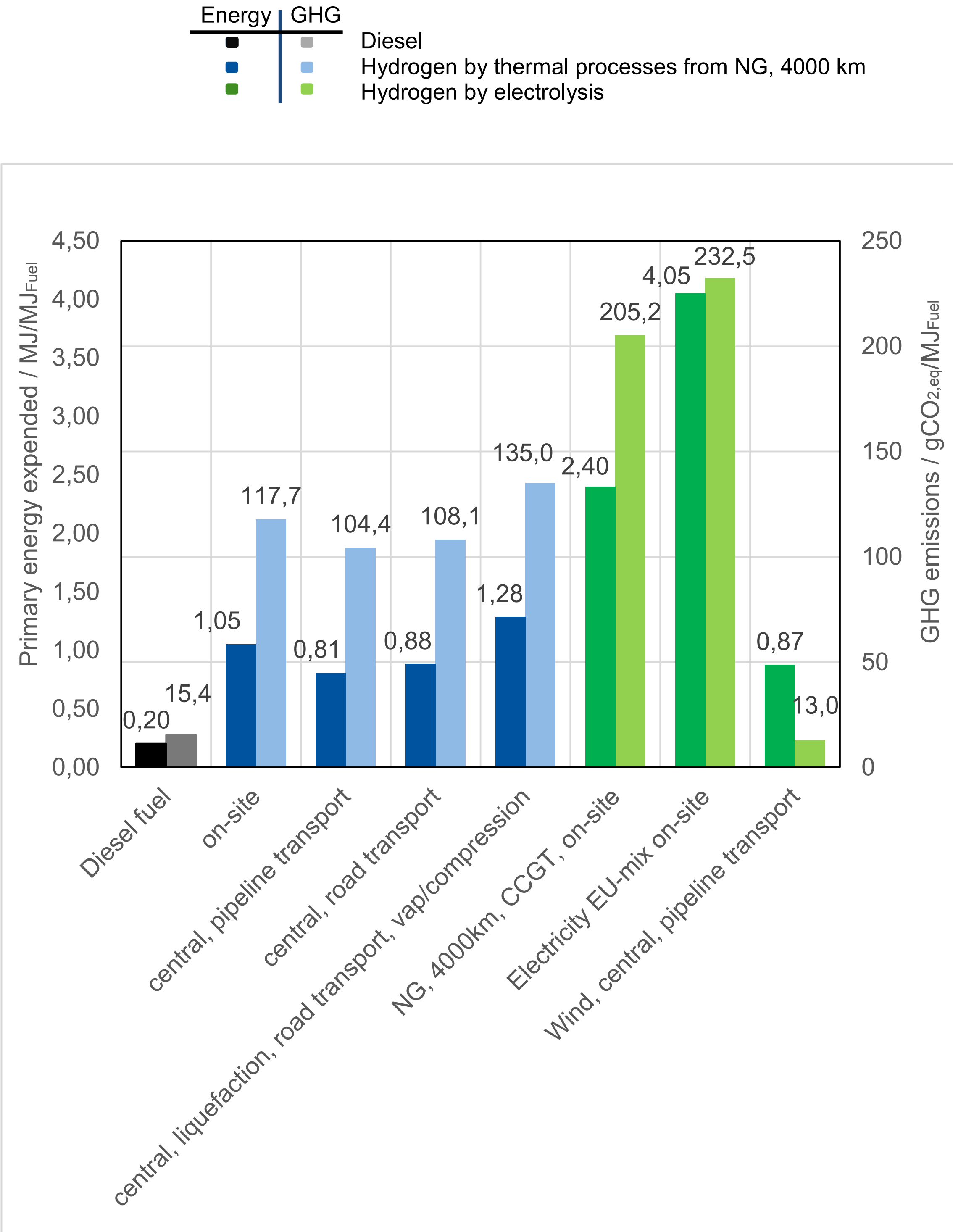

Fig. 4.4: Primary energy expended and GHG emissions producing 1 MJ_{Fuel} of fuel [Edw14]

This energy balance even worsens if the EU electricity mix is used. This is because the efficiency of more than 60 % of the combined cycle gas turbine is not reached by all other fossil energy converters. Especially lignite powered and nuclear power stations are very inefficient.

The situation changes significantly, if renewable energy is used as input to the electrolysis. This is executed using the example of wind energy. Although the primary energy effort is fairly low, it is still more than four times as great as that of diesel fuel. This is because Diesel can be produced with relatively little energy effort. However, regarding greenhouse gas emissions this form of hydrogen production can compete with diesel.

Nonetheless, these little benefits would hardly justify the technical effort and financial expenses to adopt a new technology. But the well to tank analysis is only half the story and does not suffice to evaluate a fuel. In a well to wheel analysis the efficiency of the mobile conversion is taken into account as well as the greenhouse gases emitted in the vehicle (Fig. 4.5). The original study was conducted for passenger cars, but the results can qualitatively easily be transferred to ships because the efficiency of the propulsion systems are in a comparable range. The technologies are presumed to experience certain development estimating the underlying efficiencies in 2020+. The hydrogen is used in fuel cells whereas diesel fuel is converted in a direct injection compression ignition engine.

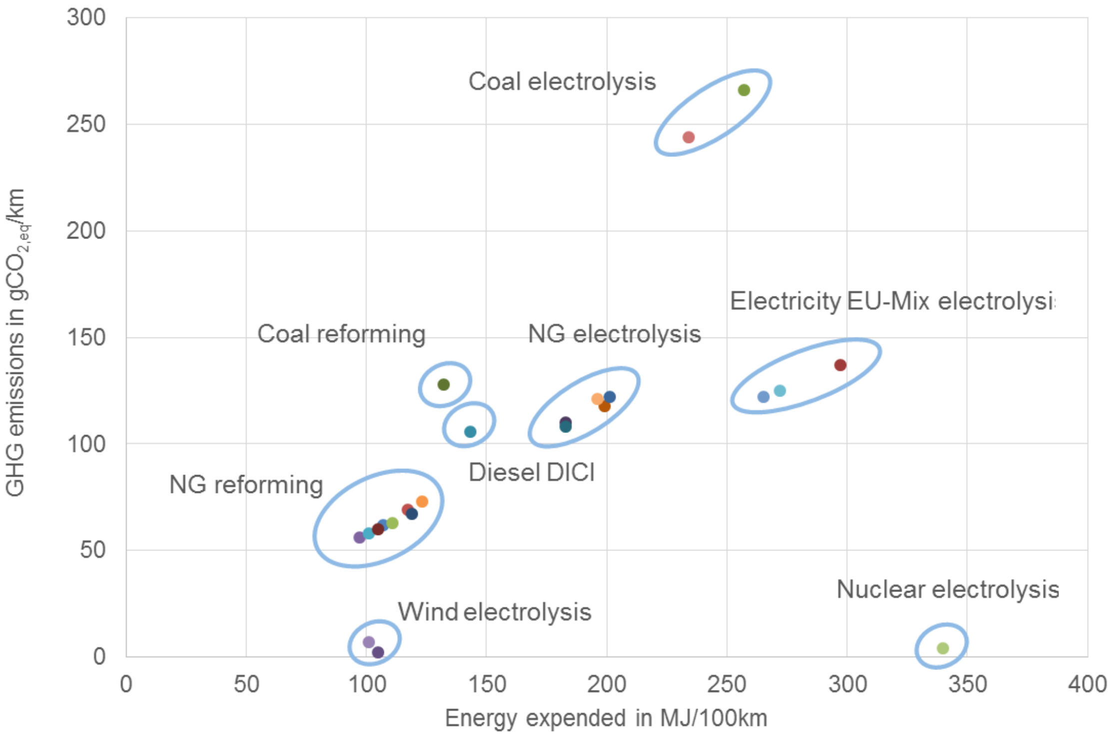

Fig. 4.5: Energy expended and Greenhouse gas emissions for 2020+ FCEV [Edw14]

In the well to wheel analysis significant advantages turn out for hydrogen produced by means of electrolysis using electricity generated by wind energy. It exhibits top values regarding the expended energy per distance driven and best values regarding greenhouse gas emissions.

Coal reforming and electrolysis are shown because significant amounts of hydrogen are produced this way in China.

Comparable to the ecological consideration it is not self-evident that hydrogen production can be economically competitive to currently used fuels. The hydrogen costs are mainly driven by the energy source. Hydrogen produced from fossil sources as coal or natural gas requires additional efforts in refinery and further treatment. In this simple view hydrogen will always be more expensive than its sources. However, a significant advantage arises in using electricity from renewable sources. In these scenarios hydrogen forms the first step in most process chains for energy storage as gaseous or liquid energy carrier. In all these scenarios significant gains in production capacity and radical changes of the market can be expected.

Regarding the current prices on fueling stations, it should be noted that the price is politically fixed nowadays and a supply to vessels could be realized much more cost efficiently so that a reduction of more than 50 % of the current fuel station price (9.5 €/kg) is reasonable.

4.1.4 Requirements and development potential

Unless produced by means of electrolysis using renewable energy sources hydrogen is not beneficial compared to diesel fuel regarding solely the aspect of primary energy use and CO_2 emissions as demonstrated in the previous section. Although hydrogen has certain benefits regarding carbon monoxide (CO), soot, hydrocarbons and partly NO_x independently from its origin, against the described background CO_2-neutral so-called green hydrogen is one major demand to ensure the reasonableness of the endeavor.

It can be expected that in the next years more and more hydrogen is very likely to be produced from renewable sources. This development is accelerated by the nuclear phase-out in Germany as well as the general intention to reduce the amount of energy originating from fossil energy carriers. With an increasing fraction of renewable energies being fed into the grid the amount of overflow energy increases more than proportionately. Besides reducing power generation, shifting power demand to periods of high power supply, storing energy is one possibility, but also a major challenge. In an integrated energy system hydrogen can act as a buffer storage for fluctuating renewable energies. The hydrogen can either be stored and converted back to electricity to be fed into the grid in periods of low power production or used as fuel for mobile purposes. Sector coupling is commonly considered a main leverage to cope with the more and more fluctuating energy supply. The existence of the many Power-to-X demonstrator projects underlines the clear trend towards an integrated energy system and hydrogen production by means of electrolysis additionally.

One demonstrating example for this kind of energy system can be found on the Orkney Islands. In the Surf ’n’ Turf project an electrolyzer powered by the tidal turbines and a wind turbine produces green hydrogen. This is transported to Kirkwall, where it is converted back into electricity by a fuel cell and used as an auxiliary power source for the inter-island ferries docked overnight. [FCB17b]

Another major aspect is the quality of the hydrogen for certain application. Especially PEM fuel cells require highly pure fuel. The quality of the hydrogen strongly depends on its source. Hydrogen produced by means of PEM-electrolysis is only contains water and oxygen apart from hydrogen. Hydrogen from reformation of fossil fuels is also contaminated by carbon dioxide, carbon monoxide and sulfurous compounds. In this context the trend towards hydrogen production from electricity clearly has a positive impact. At the same time, gas producers and gas station operators consider the requirements of fuel cells regarding fuel quality as too strict so that hydrogen costs might drop by the possibility to use lower quality fuel. [Emo13]

Notwithstanding, during the transition period hydrogen from reformed fossil fuels can serve adequately as fuel for hydrogen demonstrator ships.

4.2 Transport to and storage in the harbor

The various technologies of hydrogen storage will be explained in detail in chapter 4.3. In this chapter only the principal types, namely in compressed or liquid form and in form of liquid organic hydrogen carriers (LOHC) will be covered.

4.2.1 Current situation

The two main variants for transporting and storing hydrogen are in liquid and in gaseous form under pressure. However, also other forms are worth considering – especially for storage in the harbor.

Liquid hydrogen (LH_2) must first be liquefied in a complex process. Since the boiling temperature of hydrogen is 20.4 K, the process is carried out in cryotechnical plants. The energy used for this is, depending on the system, between 20% and 35% of the energy content of the hydrogen in relation to the lower calorific value [Mar15]. The liquid hydrogen is stored in double-walled vacuum-insulated containers at a maximum operating pressure between 5 and 12 bar [Kle10] [Eic10] [Hei06]. However, heat influx cannot be avoided, which leads to the so-called boil-off, the vaporization of hydrogen. The boil-off rate strongly depends on the tank size because the relation between tank surface and the tank volume results in the heat influx. As the vaporized hydrogen would increase the pressure inside the tank, a constant flow rate of hydrogen must be removed from the storage. In order to avoid it being wasted, this hydrogen should be used in a reasonable way. This could be a fuel cell or combustion engine or a furnace producing electricity or heat. The centrally produced liquid hydrogen is mainly distributed by truck, which can transport approx. 3600 kg hydrogen [Tam14]. Nowadays it is not uncommon that bundles of hydrogen are transported hundreds of kilometers by road. This is because hydrogen production sites for the chemical industry often solely supply their main customer. The big players in the gas market only have a small number of plants designed for supplying gas of sufficient quality to the end customer.

For the compression work from 1 bar to 700 bar or 1000 bar respectively, an energy corresponding to approx. 10% to 15% of the lower heating value of hydrogen is needed [Mar15]. Gaseous hydrogen is stored at different pressures. Gas suppliers usually offer steel cylinders and -bundles at 200 or 300 bar. In the automotive sector pressures of 350 bar in the heavy duty area and pressures of 700 bar for fuel cell cars are used. Most storage tanks consist of carbon fiber-wrapped aluminum or plastic liners.

One tremendous advantage of diesel fuel is its availability in basically every gas station around the globe. LOHC as one storage alternative offers, at least partly, the chance to use this existing infrastructure because the properties of liquid carriers are comparable to Diesel fuels.

There is no hydrogen infrastructure comparable to diesel or gasoline yet. Due to the increasing use of hydrogen in FC passenger cars, the expansion of the infrastructure will continue and be pushed ahead with the development of the market. While in 2017 in Germany 28 hydrogen gas stations were in service, in August 2018 44 public stations are in operation according to the H_2 MOBILITY roadmap their number will reach 100 by 2019 [H2M18a] and is planned to rise up to 400 gas stations in 2023. On-site reforming from natural gas is another option, as is the production of the hydrogen by electrolysis at the gas station. The refueling of ships with liquid hydrogen could be analogous to the current bunkering of inland waterway vessels with LNG, which are characterized by bunkering directly from truck to ship at an appropriate berth. With greater demand appropriate bunker stations would have to be built.

For IWT, this situation can be concluded that the supply chain favors a transition to hydrogen. Even if there is nearly no dedicated infrastructure, in contrast to the high efforts for roadside vehicles the availability of hydrogen along the major IWT routes is already given already as shown in section 4.1 and will be ensured for the future.

4.2.2 Requirements

The demand for green hydrogen includes not only the production of the hydrogen itself, but also comprises the transportation to the location of bunkering. It would not be acceptable if the ship was powered by green hydrogen that is in turn transported along the river by a diesel-powered truck. That is why on-site production is desired or central production with pipeline transportation and no or only very limited and preferably hydrogen powered road traffic.

As previously described, a transformation between compressed and liquid hydrogen requires significant amounts of energy and hence is not beneficial to the overall carbon dioxide balance. Against this background it does not make sense to convert between these two types in the harbor. This also means that, if both types of hydrogen are to be offered to ships, both need to be stored in the harbor in larger amounts unless there is a continuous supply.

The situation might be different for chemical hydrogen storage. In contrast to compressed or liquid hydrogen, LOHC for instance, which is presented in section 4.3 in more detail, is not a standard commercial product so that the base product will presumably be compressed or liquid hydrogen. As long as this is the case, it is an option to use the existent infrastructure for the mentioned standard types and to hydrogenate the carrier substance in the harbor. For efficiency reasons, the heat released in this process at temperatures between 150 °C and 250 °C should be used for heating or process purposes.

4.2.3 Development potential

The fulfillment of the requirements is facilitated by a couple of factors. More and more rather small-scale P2X locations will decrease the distance to the place of hydrogen consumption. Moreover, due to the stable interconnection with the chemical industry large scale P2X sites will primarily be situated close to waterways. Especially along the Rhine, in many ports chemical industry is located so that supply would be easiest here.

One can additionally profit from the existent infrastructure. In the Rhein-Ruhr area for instance, a 240 km long hydrogen pipeline distributes hydrogen between several producers and consumers. It covers the area between Leverkusen, Krefeld, Oberhausen, Marl and Dortmund (see Fig. 4.6) [CEW09] [Toe06] [Air18]. This pipeline could be easily used to serve the river Rhine including the principal port of Duisburg as well as several canals in the region.

Furthermore, Air Liquide operates a pipeline of 966 km in the Netherlands, Belgium, and France connecting Rozenburg, Bergen-op-Zoom, Antwerp, Gent, Brussels, Terneuzen, Charleroi, Feluy, Isbergues and Waziers [Toe06]. This pipeline could be a good basis to supply the waterways in this region.

Furthermore hydrogen gas stations for road traffic will face the same challenges of a "green" supply chain. It can be expected that solutions will be found. Thus, locations without existent pipeline infrastructure could profit from the development in this sector.

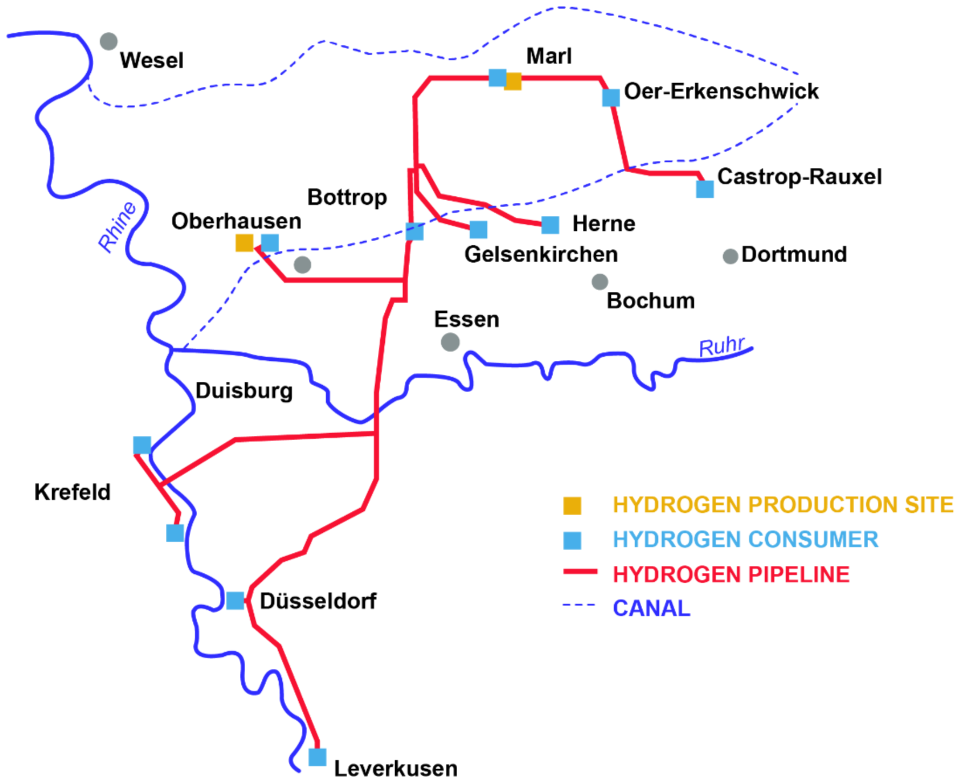

Fig. 4.6: Hydrogen pipeline in the Rhine-Ruhr area [CEW09]

4.3 Onboard storage and bunkering

First, several storage technologies are introduced. Subsequently, in section 4.3.2 they are compared regarding their energy density. This is followed by an analysis of bunkering procedures and the requirements regarding the constructional integration in sections 4.3.3 and 4.3.4, respectively.

4.3.1 Types of hydrogen storage

Hydrogen storages can be categorized into physical-based and material-based types [DOE18b]. The physical-based category comprises compressed, liquid and cryo-compressed hydrogen (see Fig. 4.7). These types and a selection of the material-based storage (liquid organic hydrogen carriers and metal hydrides) are presented in the following sections in detail.

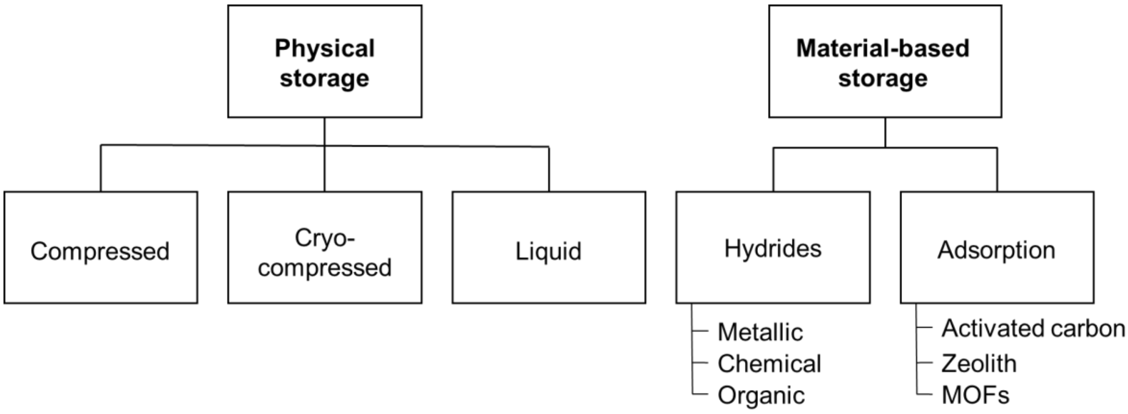

Fig. 4.7: Overview of storage technologies (according to [BMW12])

Compressed hydrogen

As mentioned before, compressed hydrogen is usually stored at pressures of up to 700 bar at ambient temperature. As only a valve is needed to control the mass flow rate, withdrawing compressed hydrogen for usage is relatively simple (see Fig. 4.8).

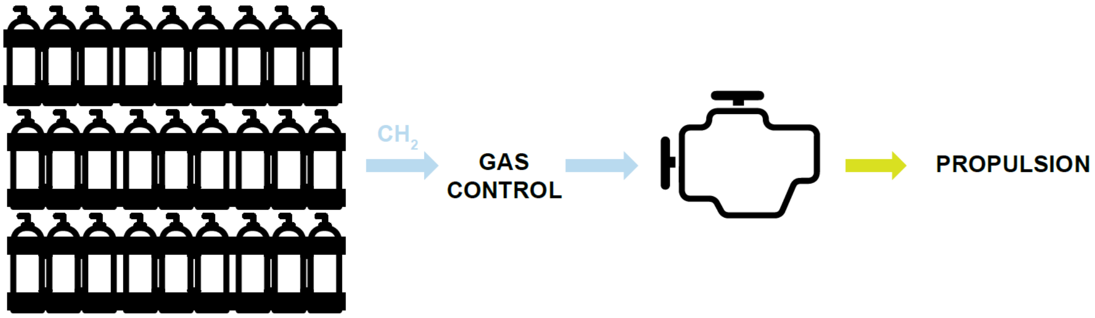

Fig. 4.8: Compressed hydrogen storage system

One innovative example of particular interest for shipping applications is to store the hydrogen in standard intermodal freight containers. This configuration allows for shortening the fueling times by facilitating a quick exchange of the entire tank. For container ships this method is an easy retrofit, because an accessible storage site of perfect dimensions is already available and accessible. A solution offered by EMS is depicted in Fig. 4.9. This 40 ft high cube container contains 162 composite vessels of 211 liters content each. The minimal and nominal working pressure as well as the maximum fill pressure are 20 bar, 500 bar and 625 bar, respectively. In a pressure range between 500 bar and 20 bar 1021 kg hydrogen can be stored in the entire 40 ft HC container. The weight of the empty vessels is 19,602 kg and the structure and rest of the container about 8 t. The price for one container is listed at approximately 900,000 €.

Fig. 4.9: EMS high-compressed hydrogen container system [EMS18]

According to ems evolves the filling time is specified as 60 g/s. Although exchanging the entire container would be preferred in most cases, this number can still serve as a rough basis for calculating the filling time for a permanently installed system. However, this can only be an estimation, since the exact filling times depend on the specific tank situation onboard the vessel including piping and the land-based capacity.

Liquid hydrogen

Liquid hydrogen is stored at temperatures below the boiling point at around 20 K at ambient to moderate pressures. To achieve optimum insulation, the tanks are double-walled. The space between the inter-meshed containers is evacuated to reduce heat transfer and the inner tank is wrapped in a multilayer insulation (MLI). Despite the heat insulation, there is a constant heat flow from outside to inside, causing the hydrogen to vaporize, as already mentioned in section 4.2.1. In consequence, the internal pressure increases over time. After reaching the maximum operating pressure, the safety valves open. In order to prevent this, the amount of vaporizing hydrogen should continuously be removed. Hence, this solution is attractive especially for applications with a constant consumption.

In combustion engines and fuel cells, the hydrogen is consumed in gaseous form, with the former requiring a higher pressure by tendency. In general, two variants are conceivable for providing the required minimum pressure.

One option is to first vaporize the liquid hydrogen in an evaporator. In a next step it is compressed to the required pressure and stored in a buffer tank, from where it is fed into the internal combustion engine or fuel cell.

The second alternative is to first compress the liquid hydrogen and vaporize it afterwards. As compressing a liquid requires less energy than compressing a gas, this is a highly promising method. Linde offers a two-stage cryo-pump in which the liquid hydrogen is compressed to 0.6 MPa in the first stage. In the second stage, the hydrogen is further compressed to maximum 90 MPa with subsequent increase of the cryogenic gas to -40 °C. According to the company Linde, the compression of liquid hydrogen requires only about 10% to 20% of the energy of a gas compressor. [BMW12]

Lower pressures can be provided by the vaporizer only. Since the vaporizer usually uses waste heat, during cold start a buffer storage for compressed hydrogen is necessary for both the high and low pressure system. The liquid hydrogen storage system is schematically depicted in Fig. 4.10.

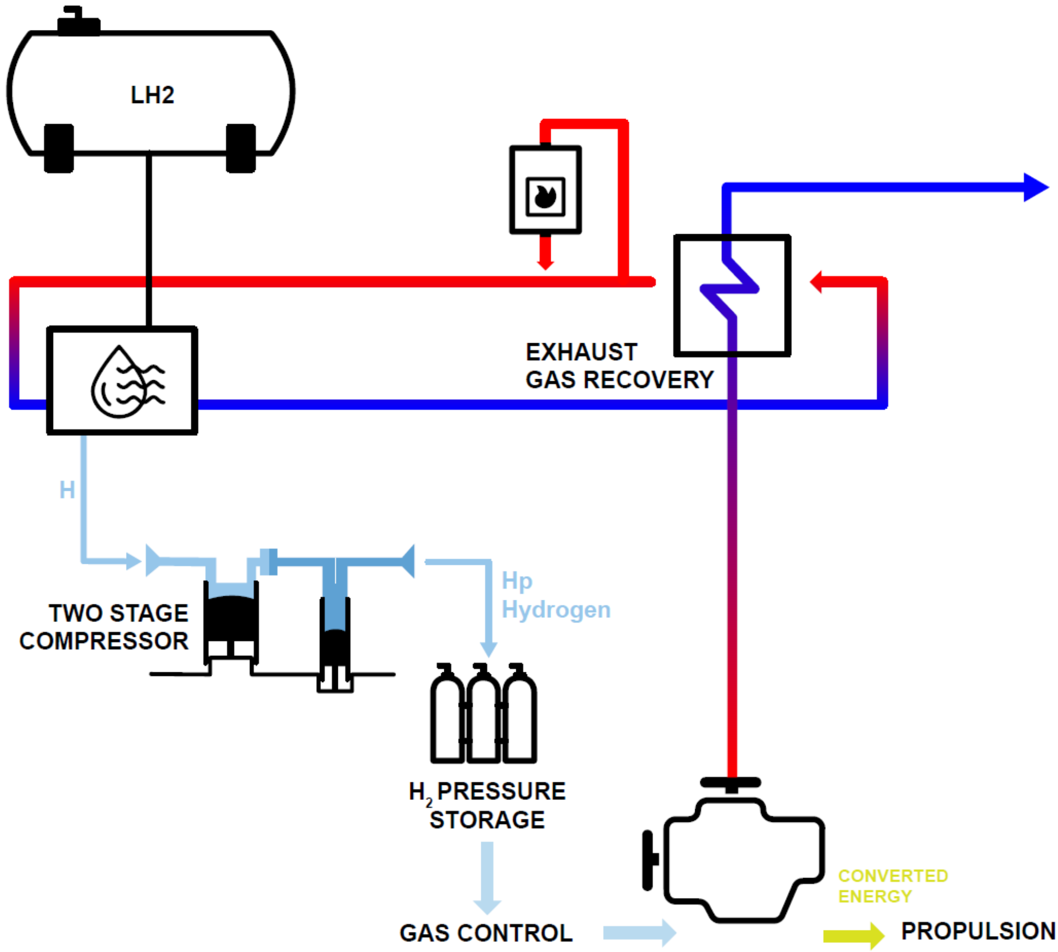

Fig. 4.10: Liquid hydrogen storage system

The filling time for a 3500 kg delivery is about 4 h pumping time after precooling the pipes for about 1 h.

Due to a lack of offers, the cost for the LH_2 storage tank can only be very roughly estimated using a formula provided in [Win89]. Converting the currency from DM to € using the official exchange rate and taking into account the general inflation rate from 1989 to 2017 of 67 % leads to

$$\text{Cost}_{\,LH_2\,storage\,tank} = \frac{14{,}500}{(\frac{V}{m^3})^{0.3}} \frac{€}{m^3} \tag{4.1}$$

Cryo-compressed hydrogen

Another method currently being in the prototype stadium is called cryo-compressed hydrogen storage and a mixture of compressed and liquid storage. The pressurized hydrogen is stored at temperatures above the boiling temperature at elevated pressure. It reaches its highest density at temperatures below -200 °C at pressures up to 1000 bar. [BMW12]

Liquid Organic Hydrogen Carriers

A liquid organic hydrogen carrier is hydrogenated and dehydrogenated to store and release the hydrogen, respectively. With no molecular hydrogen being present in the LOHC storage, the core aspect is binding the hydrogen to the carrier substance

The exothermic hydrogenation reaction proceeds between 150 and 250 °C at a pressure of over 20 bar. Per molecule of the carrier fluid ($LOHC^-$), 9 molecules of H_2 can be taken (loading of about 6.2 mass percent with hydrogen possible). The released energy of about 9 kWh_{th} / kg H_2 must be dissipated and can be used for heating or process purposes [Pre16]. The hydrogenated fluid ($LOHC^+$) can then be stored at ambient conditions. Platinum, ruthenium, rhodium, nickel or copper are used as catalysts in the hydrogenation process.

In comparison to the hydrogenation the dehydrogenation in an endothermic reaction taking place at higher temperatures between 250 °C and 320 °C, but at lower pressures between 1 and 3 bar. The low-hydrogen $LOHC^-$ can then be stored until reused for hydrogenation. For the dehydrogenation, commercial catalysts (platinum as a catalytic substance and alumina or carbon as a carrier) may be used. The power control of the releaser can be regulated by changing the LOHC mass flow rate or the reaction conditions.

The required dehydrogenation heat plays a central role. After the carrier fluid has been stored for an extended period of time, it is delivered to the releaser at ambient temperature. To heat it up to the reaction temperature, a certain amount of heat has to be supplied. One option is to recover heat from the dehydrogenated liquid and an additional gas heater. By metering temperatures and the rate of hydrogen consumption just as much hydrogen is burnt as needed. Regarding the lower heating value of 33.33 kWh/kg H_2, about one third of the hydrogen must be burnt to provide the necessary heat. This increases hydrogen consumption and hence the storage size by 50 % which is why this option is only favorable for short periods of time such as start up. This holds true even more for an electric heater. When another heat supplier such as the internal combustion engine is in operation, its exhaust gas can serve as source delivering the necessary amount of heat to maintain the dehydrogenation via a heat exchange in the exhaust gas flow. The system complexities are illustrated in Fig. 4.11.

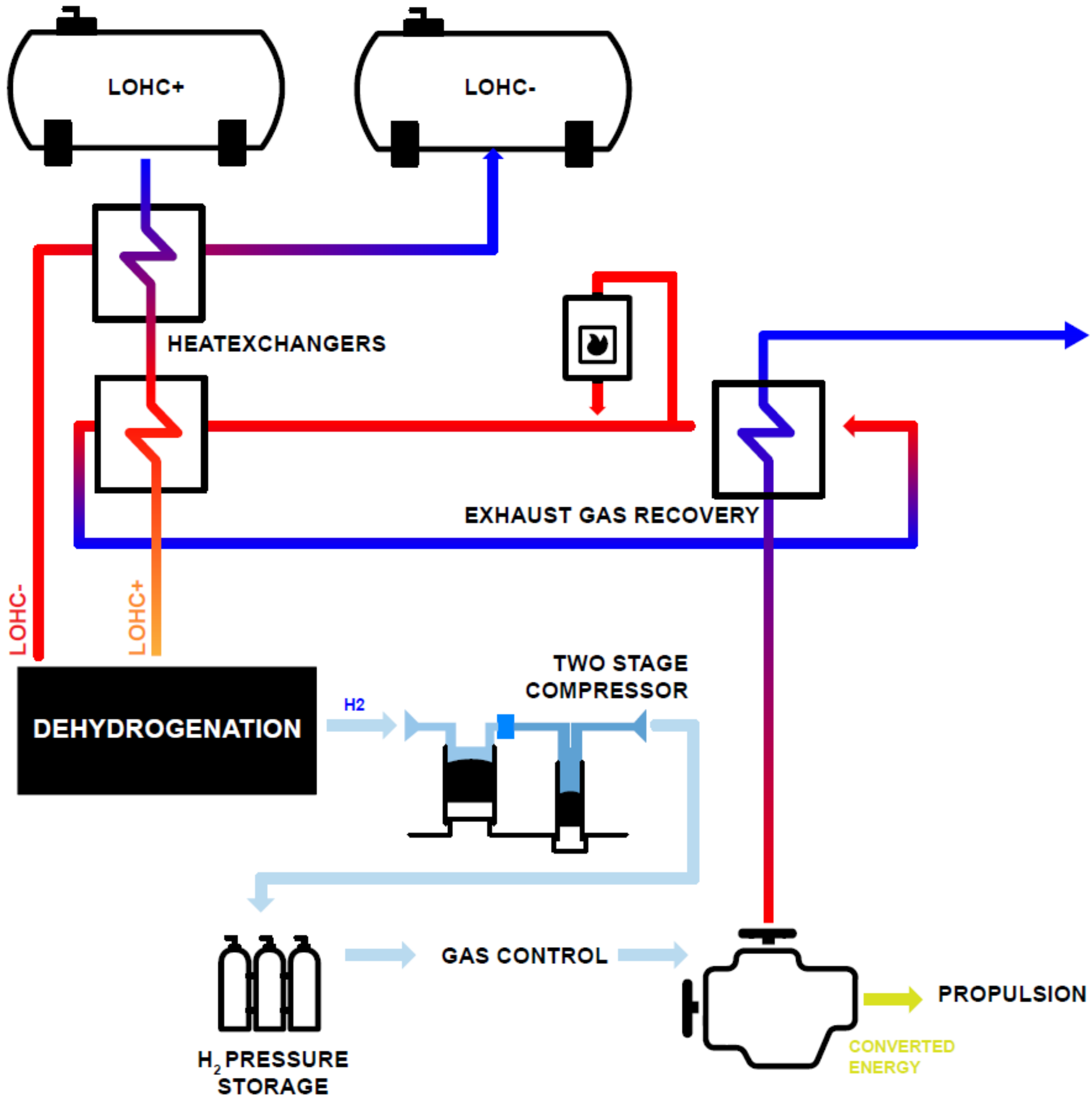

Fig. 4.11: LOHC storage system

In contrast to compressed hydrogen which can be used right away, considerable effort is necessary to purify the hydrogen to reach the quality required for fuel cell operation. When used in an internal combustion engine, the cleaning can be dispensed with.

The storage of dibenzyltoluene H0-DBT ($LOHC^-$) and perhydro-dibenzyltoluene H18-DBT ($LOHC^+$) is basically possible in all tank designs and geometries. Due to the diesel-like material class, they can be stored in conventional steel tanks. Furthermore, H0-DBT and H18-DBT are not classified as dangerous goods.

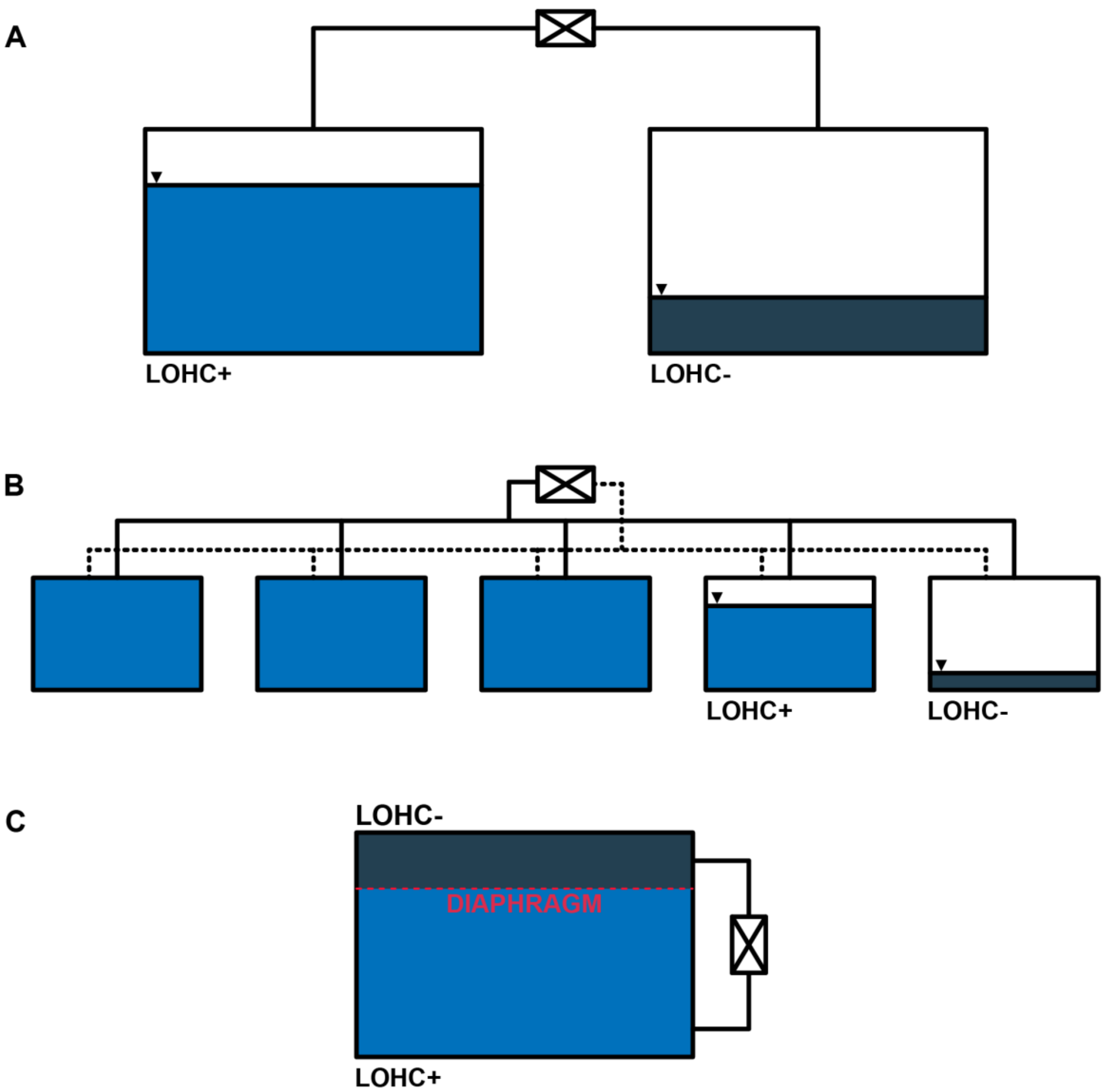

Fig. 4.12: LOHC tank configurations: two separate tanks (A), multi-chamber tanks (B), diaphragm tank (C)

Three general LOHC tank system configurations are depicted in Fig. 4.12:

1. Two separate tanks with the identical volume for $LOHC^{+}$ and $LOHC^{-}$.
2. Multi chamber tank with for example five chambers, with initially four chambers filled with $LOHC^{+}$ and one chamber for $LOHC^{-}$. This requires a complex transfer system, but decreases the “empty volume” of the tank system.
3. A diaphragm tank for storing $LOHC^{+}$ and $LOHC^{-}$ in one tank, divided by a diaphragm. Due to the similar density of $LOHC^{+}$ and $LOHC^{-}$ the installed tank volume is lowest of all three configurations.

Due to the high viscosity of H18-DBT (434 mPas at 20 °C) and H0-DBT (48 mPas at 20°C in relation to Diesel (between 2 and 4.5 mPas at 40 °C) it has to be checked whether the installed transfer pumps are capable of pumping this kind of medium.

As a guideline the existing rules and regulations from the classification societies can be used.

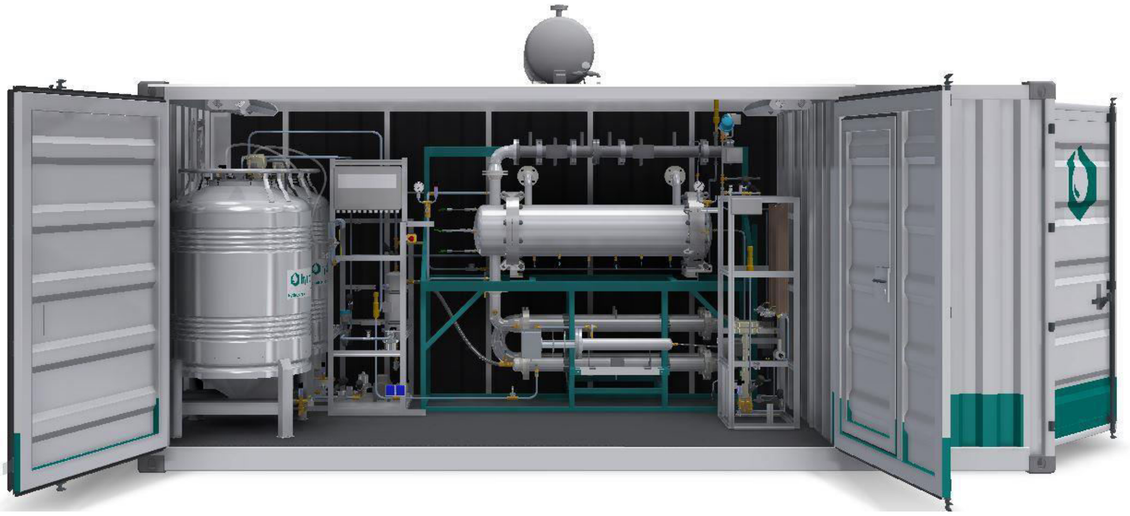

Fig. 4.13: Hydrogenious release box [Hyd16]

One company offering hydrogen LOHC storage and release systems is Hydrogenious. Their release systems (see Fig. 4.13) come in standard containers and deliver hydrogen flow rates up to 9 kg/h as specified in Table 4.1.

Table 4.1: Characteristics of the Hydrogenious release box [Hyd16]

	Series 10	Series 150	Series 250
H_2 outlet	10 Nm³/h 0.9 kg/h	150 Nm³/h 13.5 kg/h	250 Nm³/h 22.5 kg/h
$LOHC_C$	16 l/h	240 l/h	400 l/h
Heat demand	10 kW	150 kW	250 kW
H_2 outlet pressure	1 to 700 bar	1 to 700 bar	1 to 700 bar
Size	20 ft. container	30 ft. container	40 ft. container

The hydrogen release rate of the Series 250 product, 22.5 kg/h, corresponds to a chemical power of the hydrogen of 750 kW. The pressure delivered by the dehydrogenation process itself ranges at around one to three bar and does not comply with the minimum pressure demand to be fed directly into an internal combustion engine or fuel cell. To overcome this, a compressor and buffer system have to be used.

Today, the technology readiness level of LOHC storage systems can be considered to be about 6-7. Further information regarding costs and weight of the required infrastructure are not available yet.

Metal hydrides

Another method to store hydrogen is using metal hydrides. There are many metals with high variability in properties such as reaction temperatures [Kle12]. Hydrogenation on metallic molecules occurs by cleavage of the hydrogen molecules, which are then incorporated into the lattice structure of the active material.

One can differentiate between classic metal hydrides using the process of physisorption and light metal hydrides using chemisorption. [Sto15]

With the former, the loading of the metal hydride storage is an exothermic process releasing hydrogenation heat. The unloading of the metal hydride storage takes place endothermically. Heat must be supplied to keep the dehydrogenation process running. The discharge pressure and the temperature level during the unloading and loading process can be determined by the choice of the metal alloy. The heat management determines the storage rate of the uptake and release of the hydrogen.

Table 4.2: Types of metal hydrides [Buc82]

Desorption temperature	Material	Max. hydrogen storage density	Status
Low temperature -30 °C ... 100 °C	iron-, titanium and lanthanum alloys	2.2 weight-%	available
Medium temperature 100 °C … 200 °C	Complex metal hydrides, e.g. endowed NiAl-alloys	2.5 weight-%	Experimental research
High temperature >200 °C	Mg-alloys	8 weight-%	First products commercial available

In the following paragraphs the light metal hydride sodium borohydride $NaBH_4$ is presented exemplarily as one of the metal borohydrides that can be used for storing hydrogen [Zha07] [Mui11]. The sorption and desorption processes differs radically from that of the previously described classic metal hydrides.

An advantage of sodium borohydride compared to other metal borohydrides is the high theoretical, gravimetric hydrogen storage capacity of 10.8 wt%. Sodium borohydride is also one of the most stable metal hydrides to store at ambient conditions making it a safer fuel than compressed or liquefied hydrogen. The hydrogen can be released by hydrolysis of the $NaBH_4$ like shown in the equation below. This exothermic reaction takes place very slowly, but can be accelerated by adding an acid (operating at a higher pH value), by using a catalyst such as ruthenium or by increasing the temperature.

$$NaBH_4 + 2H_2O \rightarrow NaBO_2 + 4H_2 + Heat \qquad (4.2)$$

The reaction takes place in a reactor in which the $NaBH_4$ is added to the required amount of water and an accelerator. The reaction is exothermic, meaning heat is released which can be used on the ship for instance for heating purposes on-board the vessel. In the reactor the hydrogen can be separated from the by-product $NaBO_2$. It should be noted that from the start until the end of the trip the total weight of the fuel increases when the water is added.

The hydrogen can be used in a fuel cell or internal combustion engine and the by-product can be stored until being reused in the hydrogen storing process in which the $NaBO_2$ is regenerated to $NaBH_4$. This process requires energy.

An example of a configuration using sodium borohydride is shown in Fig. 4.14. In this setup the fuel and the $NaBO_2$, the so-called spent fuel, are stored in a volume exchange tank to reduce the volumetric system energy density. A catalyst is used in this case to accelerate the hydrolysis of the process. The water needed for the reaction is generated on-board by reverse osmosis and by recirculating the water from the fuel cell.

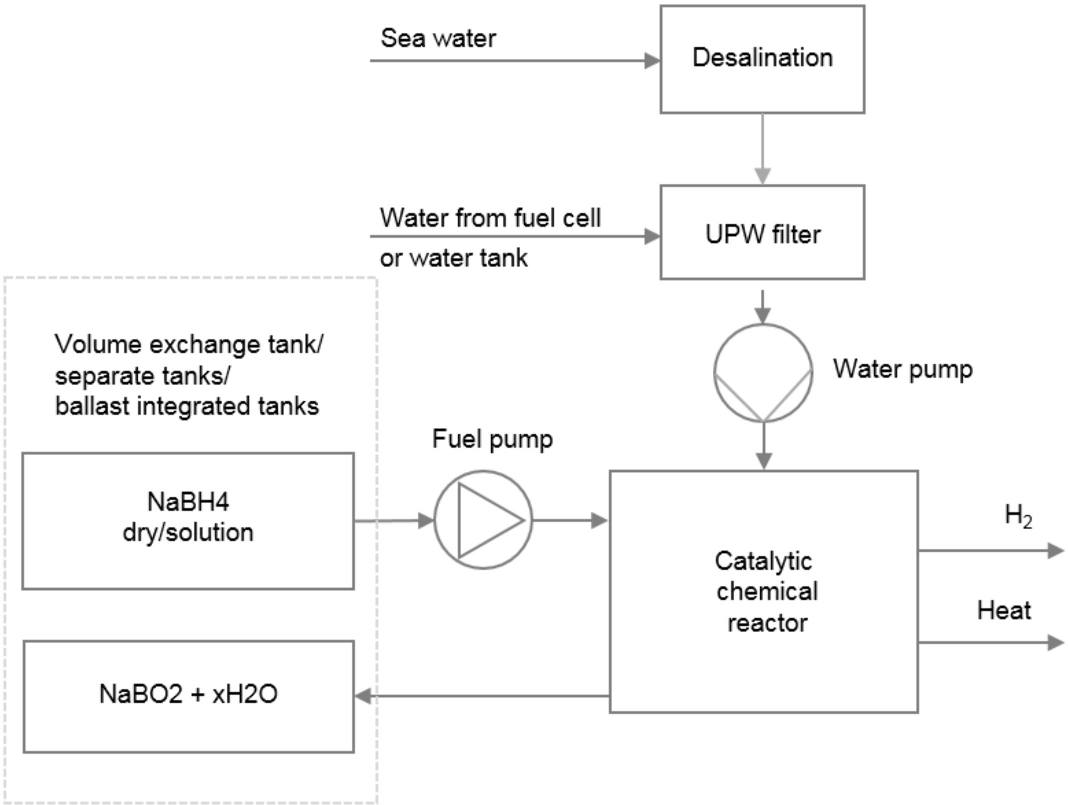

Fig. 4.14: Concept configuration of the hydrolysis of sodium borohydride using a catalyst, water generating and recirculation from the fuel cell [H2F18]

To make the sodium borohydride pumpable on and off board, it should be dissolved in a liquid such as water. To prevent the dehydrogenation reaction, a stabilizer like sodium hydroxide must be added. In this context, for dehydrogenation catalyst is crucial. [Zha07] Alternatively, using only the compact dry fuel and water generation on-board, the fuel can be handled pneumatically or as bulk by loading and unloading the tanks.

It should be mentioned that the storage densities of 10.8 wt% H_2 are only theoretical values. Real values are significantly lower because of the excess water required to dissolve the $NaBH_4$ and the $NaBO_2$ and due to the extra mass of the reaction and storage vessels. In 2007 the United States Department of Energy (DOE) target of 4.5 wt% hydrogen could not be demonstrated and the DOE had doubts that future targets could be met. [DEH07] [Mui11]

Another drawback is that the regeneration of the $NaBO_2$ to the $NaBH_4$ is extremely complex and costly. Although there have been proven alternative path ways, chemistry is still at an early stage. [Lin10] [Mui11]

Another challenge regarding metal hydrides is that they can swell up to 30 % of their original volume. The entailed tank stress has to be accommodated in tank design.

[Pra16] As metal hydride storages are not available as a large-series commercial product, reliable prices for such are unknown.

4.3.2 Energy densities

In Fig. 4.15 the volumetric and gravimetric storage densities of various fuels are plotted. The spots marked by the triangle refer to the values including the system. Compared to conventional fuels, the storage densities of all types of hydrogen storage systems are significantly lower. For diesel this is more than factor six in volume and more than factor three in weight. In Table 4.3 the storage densities of select forms of hydrogen storage are shown for more detail and compared to diesel as a reference.

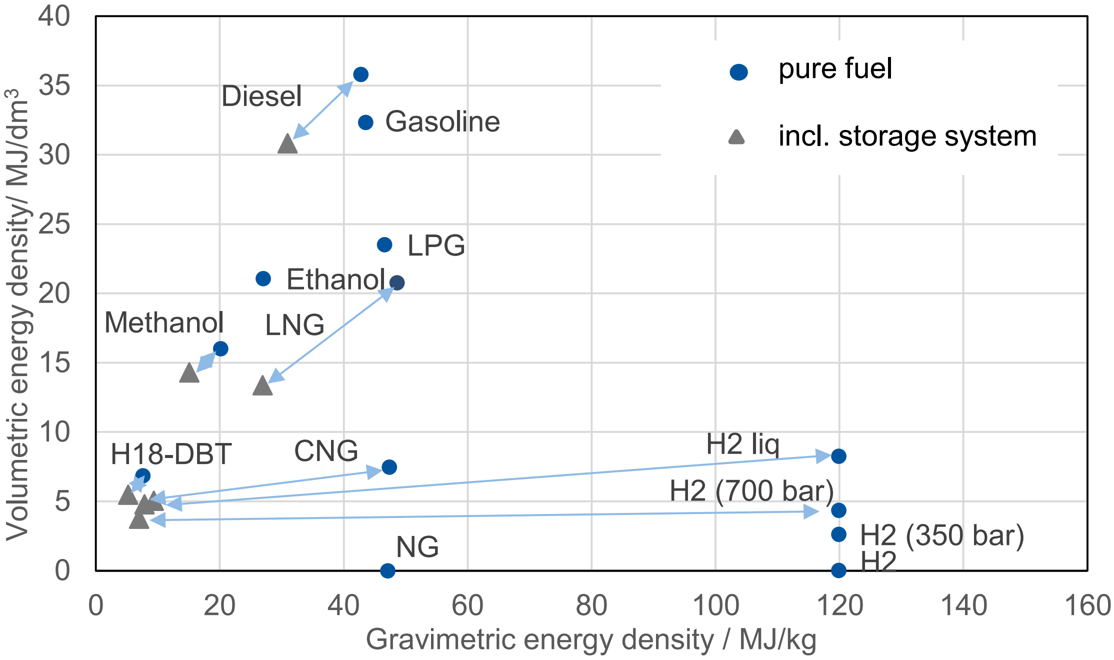

Fig. 4.15: Volumetric calorific value over gravimetric calorific value for different fuels and conditions [She17] [Bie16] [Kle10]

Table 4.3: Specific energy storage densities including the system

Fuel	Gravimetric value MJ/kg	Volumetric value MJ/dm³
Compressed H_2 (700 bar)	6.98	3.76
LH_2	9.34	5.04
LOHC (H18-DBT)	5.19	5.49
Diesel	30.92	30.84

Compressed gaseous hydrogen has the lowest system complexity, because beside the tanks only pressure reduce valves are needed. On the other hand it also has the lowest volumetric storage density.

Liquid hydrogen is by trend the most dense storage system for large amounts, but due to increasing losses and higher specific costs not suitable for storing small amounts without constant consumption. The storage density increases with an increasing storage amount. The values given in the table correspond to a storage system of about 150 m³ liquid hydrogen.

Liquid organic hydrogen carriers require the simplest tanks easily allowing for long-term storage, but they need the most complex release system.

Among the presented selection, metal hydrides are the heaviest form of hydrogen storage [Pra16]. Apart from the German submarine class U212A, only few applications are known. As a consequence, only little practical information about the effective specifications are publicly available. For these reasons metal hydrides will not be considered in the further parts of the study.

4.3.3 Bunkering

In the feasibility study on bunkering of gaseous fuels [Vog12], three different bunkering methods were identified: shore-to-ship, ship-to-ship and truck-to-ship. This is illustrated in Fig. 4.16. The prevalent method of bunkering is the bunker boat method. The arrangements between the bunker vessels and the ships can be of very different kinds: some owners have agreements with certain bunker vessels, some make their decisions under other aspects. The bunker vessels usually come alongside the IWT vessels, often during loading or unloading. For IWT ships fuel tank sizes between 15 m³ and 50 m³ are common. On average, ships bunker once a week.

LNG-fueled ships in pilot projects are usually fueled by truck-to ship bunkering, because of the small amounts of fuel they demand.

In addition to the options to bunker liquid hydrogen presented above, a direct reception of mobile tank units in the form of containers could be imagined. The full containers are loaded onto the ship and the empty ones removed later. While the ship is in motion, the hydrogen is pumped from the mobile add-on tank into the tank on the ship allowing to decrease the times of stops for refueling significantly. Today, this type of tank installed in container racks is increasingly being used as a means of transporting gaseous fuels compared to road tankers. [SGM17]

The liquid hydrogen refueling process includes inert gas purging, pipe cooling and the refueling itself. To bunker a large container with a capacity of 3500 kg LH_2, four hours of purging and cooling and one hour of refueling are required.

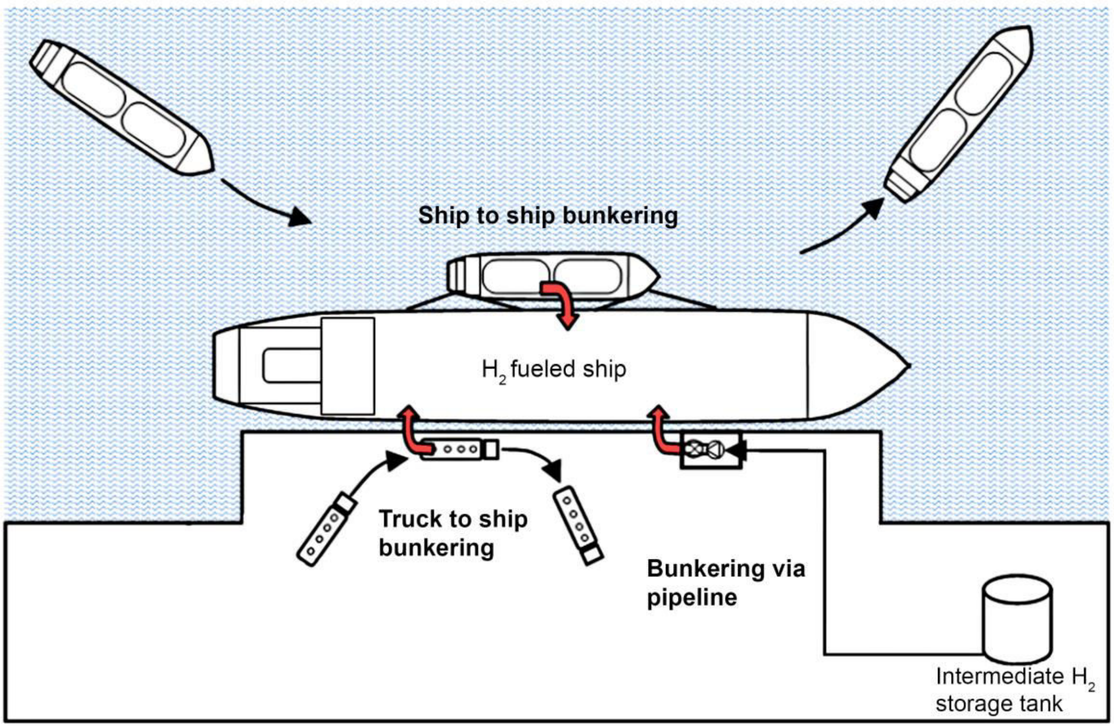

Fig. 4.16: Three possible ways of bunkering conceivable for hydrogen [Vog12].

The bunker stations consist of two hose connections; one for the hydrogen and inert gas fill and one for the cool down gas return. Each hose is equipped with a dry break coupling, an emergency release coupling, one isolating flange and gas leakage sensors.

Alternatively, bunkering can take place directly from compressed H_2 delivery trucks. The bunkering of compressed hydrogen can also take place via an exchange of whole container racks. This allows shorter waiting times. The volume flow rate of the compressed hydrogen during filling is approximately 60 g/s, as specified by ems.

The existing diesel infrastructure can be used to refuel LOHC. But the lower energy density of LOHC fuels leads to longer refueling times and larger tank volumes. This will be discussed in more detail in Chapter 4.5.1.

Due to its limited operational radius the situation differs for ferries. Truck-to-ship bunkering is usual nowadays. As long as fueling is carried out by trucks, fueling time is no critical aspect with ferries, because the diesel truck drives onto the ferry where it stays during the entire fueling process while normal operation continues. In case of hydrogen it should be ensured that the ferry operation can continue during the fueling process. Direct coupling to nearby gas stations is a beneficial option and should be considered when selecting the positions for hydrogen gas stations.

The frequency of diesel bunkering differs significantly between the considered ferries, ranging from once every two to once every four weeks. A higher frequency would be possible in order to reduce the necessary size of potential hydrogen storages. A detailed overview of the duration of bunkering with the various technologies can be found in section including an exemplary calculation for the select representative types of ships.

4.3.4 Requirements regarding constructional integration

In this subchapter, the requirements regarding the constructional integration for both hydrogen storage and energy conversion systems are dealt with, mainly related to regulatory and safety aspects.

The constructional integration poses certain basic challenges: The complex storage system raises the weight and so does the additionally needed equipment for an electrostatic discharge protected (ESD) room and a vent mast. The weight distribution being strongly dependent on the storage technique and type of ship can only be evaluated in combination with a general arrangement plan which should be covered in a follow-up study. The increased occupied space, which is in IWT the far more important criterion, is very challenging as well. When placed on deck, the maximum height defined by the desired bridge clearance also has to be respected. Moreover, other criteria have to be respected such as the requirement that the tank room has to be accessible from the open deck. In order to avoid loss of propulsion, the hydrogen propulsion system must have the same redundancy level (tanks, vaporizer, etc.) as conventional marine gasoil (MGO) ships. According to the class requirements, areas with extreme surface temperatures have to be identified

For all types of vessel, the limited air draft at the sailing route is the most important issue regarding the installation of the outlet of the pressure relief valves which will be required for the installation of a liquid hydrogen storage and compressed hydrogen (CH_2) storage tank system.

According to the IGF code chapters 6.7.2.7 and 6.7.2.8, the outlets from the pressure relief valves shall normally be located at least 10 m from the nearest:

1. air intake, air outlet or opening to accommodation, service and control spaces, or other non-hazardous area; and
2. exhaust outlet from machinery installations.

Each pressure relief valve installed on a liquefied gas fuel tank shall be connected to a venting system, which shall be:

1. constructed in a way that the discharge will be unimpeded and normally be directed vertically upwards at the exit;
2. arranged to minimize the possibility of water or snow entering the vent system; and

3. arranged such that the height of vent exits shall normally not be less than B/3 or 6 m, whichever is the greater, above the weather deck and 6 m above working areas and walkways. However, vent mast height could be limited to lower value according to special consideration by the administration.

It has to be checked in detail in a follow-up study if the required distances can be reduced by presenting the results of a dispersion analysis to the administration for evaluation.

In the IGF code Chapter 12.5 three hazardous area zones are defined:

Hazardous Zone 0

This zone includes, but is not limited to the interiors of fuel tanks, any pipework for pressure-relief or other venting systems for fuel tanks, pipes and equipment containing fuel.

Hazardous Zone 1

This zone includes, but is not limited to:

1. tank connection spaces, fuel storage hold spaces and interbarrier spaces;
2. fuel preparation room arranged with ventilation according to 13.6; areas on open deck, or semi-enclosed spaces on deck, within 3 m of any fuel tank outlet, gas or vapor outlet, bunker manifold valve, other fuel valves, fuel pipe flange, fuel preparation room ventilation outlets and fuel tank openings for pressure release provided to permit the flow of small volumes of gas or vapor mixtures caused by thermal variation;
3. areas on open deck or semi-enclosed spaces on deck, within 1.5 m of fuel preparation room entrances, fuel preparation room ventilation inlets and other openings into zone 1 spaces;
4. areas on the open deck within spillage coamings surrounding gas bunker manifold valves and 3 m beyond these, up to a height of 2.4 m above the deck;
5. enclosed or semi-enclosed spaces in which pipes containing fuel are located, e.g. ducts around fuel pipes, semi-enclosed bunkering stations
6. the ESD-protected machinery space is considered a non-hazardous area during normal operation, but requires the equipment mandatory to be certified as suitable for zone 1 in case a gas leakage is detected.
7. a space protected by an airlock is considered as non-hazardous area during normal operation, but requires the equipment mandatory to be certified as suitable for zone 1 in case of a loss in differential pressure between the protected space and the hazardous area.
8. except for type C tanks, an area within 2.4 m of the outer surface of a fuel containment system where such surface is exposed to the weather

Hazardous Zone 2

This zone includes, but is not limited to areas within 1.5 m surrounding open or semi-enclosed spaces of zone 1 as well as a space containing bolted hatches to the tank connection space.

To identify the hazardous zones a hazardous area plan is mandatory to define the installation of the electrical equipment, ventilation systems and passenger accommodation spaces. At this stage no general arrangement plan is available and it is not possible to prepare the hazardous area plan for the vessel types.

In the IGF code chapter 6.6.4 the storage of compressed gas is normally not acceptable but may be permitted after special consideration and approval from the administration.

Machinery space concepts

The IGF code describes two alternative concepts for the machinery space:

1. Gas safe machinery space
2. ESD protected machinery space

For the gas safe machinery space a single failure in the fuel system should not lead to a gas release into the machinery space. That means that the gas pipes have to be double walled piping, also at the internal combustion engine (ICE).

ESD protection should be limited to machinery spaces that are certified for periodically unattended operation. The following minimum arrangement shall be provided:

- Gas detector
- Shut off valve
- Redundancy
- Efficient ventilation

Gas pipes without gastight external enclosure may be accepted under the following restrictions (IGF Code chapter 6.6.3)

- Engines for generating propulsion power and electric power shall be located in two or more machinery spaces not having any common boundaries unless it can be documented that a single casualty will not affect both spaces.
- The gas machinery space shall contain only a minimum of such necessary equipment, components and systems as are required to ensure that the gas machinery maintains its function
- A fixed gas detection system shall be fitted arranged to automatically shut down the gas supply, and disconnect all electrical equipment or installations not of a certified safe type.

Without doubt the gas safe machinery space is the target for a refit or new building to avoid extremely complex arrangements regarding the location of the electrical equipment, ventilation and main engines / main generators.

4.4 Energy conversion

Onboard the vessels, hydrogen can either be converted to the required form of energy by an internal combustion engine (either direct drive or in combination with a genset and an electric motor; see section 4.4.1) or a fuel cell and an electric motor, see section 4.4.2. When comparing ICEs and FCs, one must distinguish between mechanical and electrical energy. Internal combustion engines provide mechanical energy, whereas fuel cells directly produce electricity. Power used for propulsion is mechanical power, whereas most auxiliary consumers demand electrical energy. Conversion between these forms always comes with losses.

4.4.1 Internal Combustion Engine

The conversion of hydrogen to mechanical energy using internal combustion engines (ICE) seems beneficial for several reasons. Especially applications requiring a high propulsion power and low energy consumption for auxiliaries can profit with a direct conversion.

The majority of currently available propulsion systems in inland waterway vessels are based on internal combustion engines. The use of hydrogen as fuel offers the possibility to adapt existing engine concepts to hydrogen beside the new design of engines dedicated to hydrogen as fuel.

The properties of hydrogen as fuel differ significantly from current fuels so that several changes in the setup of a combustion engine are required.

- Injection System
- Turbocharger and intercooler
- Ignition system
- Lubrication system
- Cooling system
- Valvetrain
- Compression ratio
- Crankcase ventilation

Whereas changes in injection, charging and ignition are mandatory to realize an H_2-ICE without lack of performance the further mentioned points need to be adapted if zero emission combustion shall be realized. The most important system within the aforementioned is the injection system. In principle, two main approaches can be considered. One is the injection into the intake manifold leading to a mixture formation outside of the combustion chamber. The second one is the direct injection into the combustion chamber and an internal mixture formation.

Injection into the manifold:

- Technically less demanding
- More suitable for retrofit approaches
- Reduction of cylinder charge
- Accurate timing to valvetrain required to avoid backfire

The integration of manifold fuel injection systems does not require any changes to the cylinder head. They can be mounted on the intake manifold directly upstream the intake valves and so they are more suitable for retrofitting existing engines. To avoid an ignitable mixture in the intake that could lead to backfire the injection timing must accurately be coupled to the intake valve opening time. The high volume of injected H_2 replaces up to 30 % of the air charge compared to a conventional engine running on diesel fuel. This reduction of cylinder charge directly reduces the achievable engine power. As countermeasure an adaption of the charging system is required. According to [SAE03] an additional boost pressure of 850 mbar is sufficient to realize constant power output. Another countermeasure can be the use of cryogenic hydrogen (if LH_2 is used) that would cool the charge during injection resulting in a rising charge density. Injection systems for H_2 port fuel injection are meanwhile available (e.g. from 2G Energy AG)

Direct injection

- High technical effort for adaption of engine design
- Complex technology
- High gas pressures compared to port fuel injection
- No influence on cylinder charge
- Reduced risk of backfire
- Reduced H_2 slip

Most of the major demerits of port fuel injection systems can be solved using direct injection systems. The injection of hydrogen into the cylinder during compression stroke does not influence the cylinder charge and avoids any H_2 in the intake manifold so that the risk of backfire is drastically reduced. A typical cylinder head design of a combustion engine does not allow significant changes like the setup of an additional injector because the available space is used for optimized valve positioning as well as coolant and lubrication channels. This leads to a higher effort for the mounting of an injection and an ignition system into an existing design.

To use hydrogen in internal combustion engines an ignition system is required. This system has to be added if a compression ignition engine is the base for a conversion. Compared to other gaseous fuels like natural gas, hydrogen has the advantage of high flame velocities and good ignitability which allow the use of spark plugs also for large bore engine designs. The heat rating of these spark plugs has to be selected carefully to match the combustion parameters. As a result of the very clean H_2 combustion no deposits on spark plugs are expected so that colder plugs could be used and the maintenance intervals could be extended.

To realize a comparable power and dynamic behavior as a diesel powered engine an exchange or modification of the charging system is necessary. Especially in low end torque (low engine speed high torque) higher boosting pressures have to be realized. In retrofit applications the turbocharger has to be exchanged or a charger has to be added if a naturally aspired engine is used as base.

The properties of hydrogen as fuel enable nearly zero emission combustion concepts. Emissions of carbon monoxide, hydrocarbons and particulates are fully oil borne if hydrogen is used as fuel. Compared to hydrocarbon fuels these emissions are initially very low. To further reduce these emissions changes in the lubrication system have to be considered. These measures include changes in crankcase ventilation, valve shaft sealing and also piston rings which shall be considered in the design of a dedicated H_2 engine but would be too costly in retrofit approaches. The emission level for NO_x emissions is comparable to a diesel or gasoline engine or even higher. To reduce NO_x emissions exhaust gas recirculation (EGR) as well as lean combustion can be used. The high ignitability of hydrogen air mixtures allow air to fuel ratios of $\lambda > 2$. In such lean conditions the NO_x emissions are close to the detection limit. In combination with direct injection systems this can be used to unthrottle the engine and use the efficiency benefits. Due to the very clean combustion EGR could be adapted much easier and so it can be used for NO_x reduction and unthrottling.

Considering the minimum necessary modifications to realize a reliable, efficient and low emission engine operation, add-on costs of 20% are valued to be reasonable. The budget prices in Table 4.4 have been provided by Zeppelin Power Systems GmbH & Co. KG incl. the gear box.

Table 4.4: Estimated costs for ICE incl. gear box and modifications for hydrogen operation

Ship type	Engine model	Power kW	Total cost, standard diesel fuel version k€	Total cost incl. Modification for hydrogen operation k€
Cargo ship	3512C-HD	1x 1305	370	444
Cabin vessel	C32 C18	2x 940 2x 430	500 240	600 288
Rhine ferry	C18	1x 339	120	144
Pushed convoy	3512C-HD	3x 1425	1110	1332

4.4.2 Fuel cell

Besides converting the chemical energy of the fuel to mechanical energy by means of combustions engines, it can also be converted to electrical energy in a fuel cell.

As fuel cells do not deliver mechanical energy as needed for propulsion, they have to be combined with an electric engine. Because electric motors require peak power only in a limited period of time, fuel cell systems are often decoupled from the propulsion engine by a buffer battery. This allows for decreasing the size of the fuel cell system, a more flexible engine operation and less dynamic fuel cell operation alleviating degradation. Essential for the sizing of the fuel cell system and the battery storage is the load profile. It is the basis for determining how to distribute the load on the battery and the fuel cell and to determine which capacity of the buffer battery is reasonable. The battery can be dimensioned the smaller, the shorter the periods of high power consumption and the more homogenous the load profile. On the downside, the battery charging and discharging comes along with energy losses.

Due to the absence of high-temperature combustion, NO_x emissions are minimized. The oscillation-free operation reduces vibrations compared to internal combustion engines. This does of course not affect vibrations caused by the propeller. As fuel cells do not use thermodynamic cycles, the Carnot efficiency does not apply. Whereas the efficiency of combustion engines decreases at part load, fuel cells exhibit proper part load characteristics. Two effects come to play: The cells themselves perform the more efficiently, the smaller the load. At very little loads, however, the mechanical losses of the auxiliary components dominate consuming a lot to all of the cell power [Pay09] [Tho01].

On the other hand, at high loads, the cell losses dominate, significantly reducing the system efficiency. In consequence, there is a compromise to be found between oversizing the fuel cell system, which means higher weight, space and costs, or accepting limitations of the system efficiency. These effects are illustrated in Fig. 4.17 showing the efficiencies of a fuel cells stack and system as well as those of a Diesel and Otto engine as a function of power.

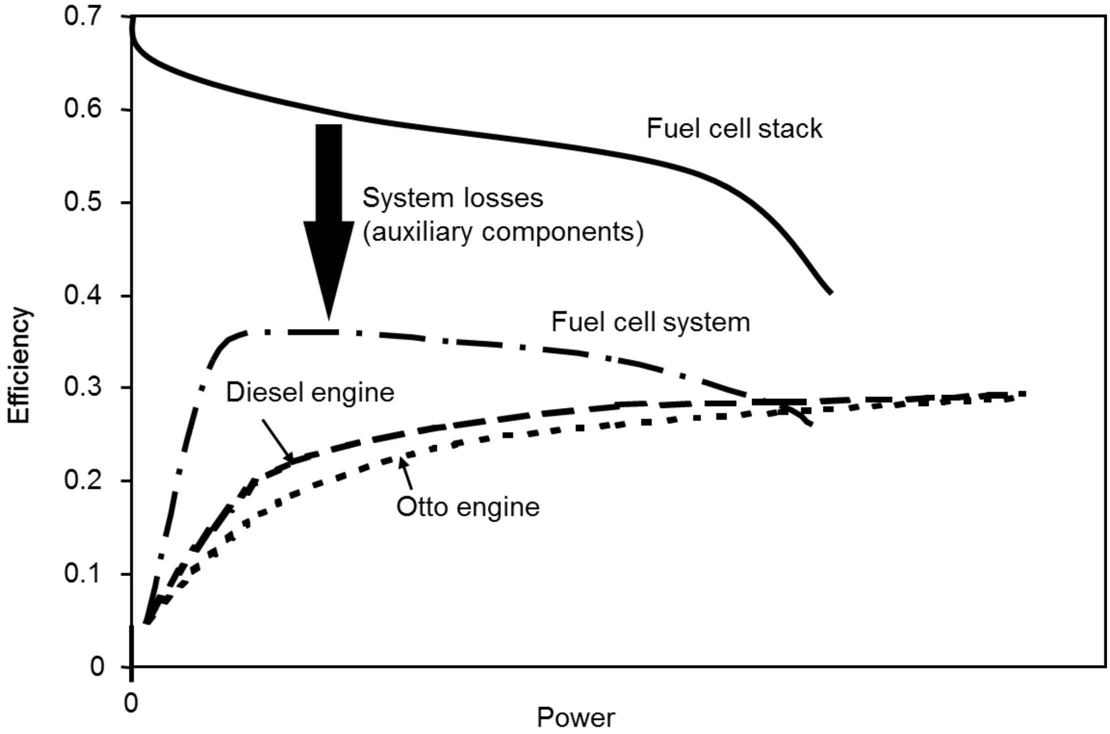

Fig. 4.17: Efficiency of fuel cell systems

Furthermore, fuel cell systems have a modular nature and their electrochemical performance tends to be independent of the system size. However, the larger the cell, the higher the concentrations losses along the flow channels and the lower the performance. Also temperature distribution is affected by the stack size. At given stack sizes, scaling effects exclusively apply to auxiliary components such as blowers, pumps and electricity converters. Like internal combustion engines used for power generation, fuel cell systems can be physically distributed and modularly operated.

Finally, the fuel cells themselves tend to degrade rather than fail. Although regular inspection, maintenance or component/stack replacement may be required, fuel cells are expected to offer good reliability and availability. Mechanical actuators like valves, compressors and pumps are subject to their normal failure. If scaling effects of auxiliary components are used with the level of redundancy being reduced at the same time, the failure of an auxiliary component like a compressor or a valve results in a complete system failure. So again, a compromise has to be found between a high efficiency of auxiliary components or their full redundancy.

There is quite a variety of fuel cell systems, but only the most promising candidates will be dealt with in this study. It appears that there is a preference for PEMFC and SOFC when regarding maritime applications [Tro17]. Several relevant characteristics are presented in Table 4.5.

Table 4.5: Overview of various characteristics of fuel cell systems relevant for maritime applications, according to [Bie16] and [Led95]

	LT-PEMFC	**SOFC**
Operating temperature (˚C)	70 - 100	500-1000
Common electrolyte	Polymer membrane	Y_2O_3 stabilized ZrO_2
El. System efficiency (LHV)	40-60	55
Fuel	H_2	light hydrocarbons (CNG, LNG), H_2, CO,
Fuel purity	99.999 %, e.g. SAE J-2719	e.g. S<20 ppm
Internal reforming	No	Yes
Gravimetric power density (W/kg)	250-1000	20-230
Volumetric power density (W/l)	300-500	8-60
Life time	5 k to 20 k hours	10 k to 40 k hours
Start-up time	<30 seconds	30 minutes to hours
Load transients (0 to 100%)	<10 seconds	<15 minutes
Capital cost today ($/kW)	>1000	3500-15,000
Cooling	Water cooling	Air cooling
Waste heat recovery	-	+

Comparing PEMFC and SOFC, several differences can be observed:

LT-PEMFCs are operated at relatively modest temperatures, between 70 and 100°C. This type of fuel cells is readily available, has a high power density, is capable of performing a quick start-up and offers good dynamic performance. However, it requires high purity hydrogen and is vulnerable to impurities like Sulphur. In addition, only low grade waste heat can be recovered due to its limited operating temperature [Mek12].

SOFCs operate at relatively high temperatures between 500 °C and 1000°C and have a high tolerance towards non H_2 fuels and impurities. Moreover, the high operating temperature enables the recovery of high temperature waste heat, e.g. in Stirling or organic Rankine cycles, adsorption chillers or to generate process steam [Ghi11]. The air-cooling, though, is rather disadvantageous in this context, because air has lower heat capacities and impedes heat transfer compared to water. The downside of these fuel cells is that they are relatively expensive, have low power density and a lower technology readiness level. Due to the long start-ups and the mechanical stress they do not allow dynamic operation. Their main features cases are summarized in Table 4.6.

Table 4.6: Comparison LT-PEMFC and SOFC regarding applications and characteristics based on [DOE18a]

Fuel cell type	**LT-PEMFC**	**SOFC**
Applications	Backup power Portable power Distributed generation Mobility	Auxiliary power Domestic electric power
Advantages	Solid electrolyte reduces corrosion and electrolyte management problems Low temperature Quick start-up and load following	Fuel flexibility Solid electrolyte Waste heat usage possible (combined heat and power)
Challenges	Expensive catalysts Sensitive to fuel impurities Water management complicated	High temperature corrosion and breakdown of cell components Long start-up time Limited number of start-stop cycles

Due to the fast hydrogen oxidation kinetics fuel cells run effectively on hydrogen. This is especially true for low temperature fuel cells, whereas high temperature fuel cells also run on methane and CO which are converted internally to hydrogen-rich gas. As emphasis is on hydrogen as fuel and replacement for diesel, other logistic fuels like natural gas

(NG), methanol (MeOH), dimethyl ether (DME), and ammonia (NH_3) will not be discussed here.

Currently there are no SOFC fuel cells available that are designed for pure hydrogen operation [Pra16], although this would be possible from a technical point of view. One reason is that the major advantage of SOFC technology is the flexibility regarding various kinds of fuels which come along with a couple of disadvantages, as mentioned. This makes SOFCs attractive for stationary operations in location where fuels like natural gas are available, whereas in other applications like the automotive sector in which pure hydrogen is available or desired PEM fuel cells are commonly preferred.

As known, there are many suppliers of different types of fuel cells. In Fig. 4.7 a selection of fuel cell suppliers is listed. It was attempted to list suppliers which are able to provide fuel cells for marine applications incl. sufficient power. Not included in this comparison are costs, an important criterion for selecting a system. It is salient that the fuel cell system offered by Powercell is advertised with an energy density four times as high as that of established competitors. It should be noted that this is not a series, but a prototype product whose long-term functionality still is to be proven.

Table 4.7: Select market available fuel cell systems as specified by the manufacturers

Manufacturer	Hydrogenics	Proton Motor	Powercell	Ballard	HyMove
Country of origin	Canada	Germany	Sweden	Canada	Netherlands
Support	Germany	Germany	Sweden	Denmark	Netherlands
Power/kW_e	90	65	(1) 100 (2) 3 x 30	100	30
Maximum system energy efficiency	Low load: 55 % Full load: 40 %	55 %	>53 %	54 %	Low load >60 % Full load: 56 % (initial) 48 % (end of life)
Certification		CE conformity		ISO6469-2:2009 ISO6469-3:2009 ISO23273:2013	ECE 79/2009 ECE 406/2010 R100 R10
Dimensions/mm	1582 x 1085 x 346	1172 x 434 x 277 (FC module) 1040 x 915 x 277 (air & coolant module)	(1) 750 x 750 x 520 (2) 630 x 405 x 740	1200 x 869 x 506 (FC module) 737 x 529 x 379 (coolant kit) 676 x 418 x 352 (air kit)	1500 x 800 x 500
Weight	360 kg incl. air module, excl. coolant pump	259 kg incl. air & coolant modules	(1) 98 kg excl. enclosure (2) 120 kg	285 kg (FC module) 44 kg (coolant kit) 61 kg (air kit)	450 kg incl. frame

4.4.3 Gravimetric and monetary comparison of combustion engines and fuel cells

In Table 4.8 and Table 4.9 the weights and dimensions of marine diesel engines of shaft powers of 374 kW and 749 kW, respectively, are compared to those of fuel cells. The data for the latter are scaled accordingly, and do neither include DC/DC converters, batteries, inverters and electric motors, nor the losses in these components. In the rightmost columns the weight and volume of these components including casings are roughly estimated based on experience from automotive parts. As no information on the dimensions of the gear was available, its volumes are estimated assuming the percental gain in weight and volume to be the same.

The weight and dimensions differ by a factor up to higher than four between the established fuel cell systems and the innovative low-weight prototype product. Although the properties of the presented prototype are unique on the market, one can still detect trends towards lighter and smaller fuel cell systems. Weight and volume of conventional diesel engines range between the shown compact and conventional fuel cell systems. For marine diesel engines low weight is no primary design criterion, but stress reliability and durability even under the toughest conditions.

Table 4.8: Weight and dimensions of a 374 kW marine diesel engine and various fuel cell systems (*estimation)

	Yanmar 6CXBM-GT		**Powercell**	**Ballard**	**Hydro genics**	**FC DC/DC, Battery, inverter, el. motor**
	Excl. Gear	Incl. Gear	scaled; excl. DC/DC, battery, el. motor			
Volume / m^3	1.24	1.54*	1.09	2.89	2.47	0.3
Weight / kg (dry)	856	1060	367	1458	1496	400

Table 4.9: Weight and dimensions of a 749 kW marine diesel engine and various fuel cell systems (*estimation)

	Yanmar 6AYEM-GT		Powercell	Ballard	Hydro-genics	FC DC/DC, Battery, Inverter, el. motor
	Excl. Gear	Incl. Gear	scaled; excl. DC/DC, battery, el. Motor			
Volume / m^3	3.74	4.72*	2.19	5.80	4.94	0.6
Weight / kg (dry)	2418	3050	734	2921	2996	800

The price for a conventional 100 kW fuel cell system currently ranges around 150,000 € excluding battery and electric motor. For 940 kW this adds up to a price of 1,400,000 €. This compares to 300,000 € for the engine Zeppelin C32 of same rated power including the modifications for hydrogen operation and gear box (compare to Table 4.4).

4.5 Application cases

Based on the analyses in the previous sections of this chapter, the most promising technologies are to be identified. This is executed for the exemplary vessels on their typical routes. As some options could be excluded right-away, for example because the type of storage, might be incompatible with the situation onboard the specific ship, first an analysis of the boundary conditions is carried out in section 4.5.1. In sections 4.5.2 to 4.5.5 the technology applications are evaluated systematically. To do so, the requirements of each type of vessel are contrasted to the features of the technologies in matrix form resulting in the suggested technology selection in section 4.5.6.

4.5.1 Boundary conditions

In this section the storage sizes for the exemplary ships running on the exemplary routes as well as the corresponding fueling times are calculated.

For the type of ships defined in chapter 2 typical routes and operating profiles are identified. For the defined ships and routes, the hydrogen consumption is calculated for the case of energy conversion in an internal combustion engine at a constant efficiency of 42 %. Since the system efficiency of fuel cells is in a comparable range, the results also represent the tank size when applying this way of energy conversion. The biggest source of inaccuracy is without doubt the hydrogen consumption as a result of the load profile that varies strongly depending on the very specific conditions.

The volume of the liquid hydrogen and the LOHC is calculated using the densities of 70.79 kg/m³ for LH_2 and 56.36 kg_{H2}/m^3_{LOHC}, respectively.

To determine the volume of the liquid hydrogen tank, for a given amount of hydrogen the dimensions of a cylinder leading to the lowest surface to volume ratio are determined. An insulation of 40 cm is added on all sides. It is clear that this just a rough estimation and that the actual volume is also determined by the concrete size of the tanks onboard the ship.

The tank volume of the LOHC is incorporated in this calculation by an extra 20 % taking into account the "empty" volume of a multi-chamber storage system. The calculation is restricted to the multi-chamber configuration because it offers a reasonable compromise between volume and constructional effort. For example, using a six-chamber-tank the empty volume is limited to 20 % of the stored liquid. In many cases the existent storage tanks could be used. The size of the spacious hydrogen release system for the LOHC storage depends on power instead of energy. It is estimated using the maximum propulsion power. Depending on the time this maximum power is demanded, it is worth considering to replace some of the release units by buffer storages in a system optimization leading to lower space, weight and costs.

For calculating the storage volume of compressed hydrogen, the number of required ems 40 ft intermodal containers is determined.

Whereas for conventional ships traveling on the Rhine it is not uncommon to refuel only at the start of each roundtrip in Rotterdam e.g., the option of refueling along the way should be explicitly considered in this study. Thus, in the calculation, it is differentiated between upstream, downstream and roundtrip, because at least at the destination of the upstream trip refueling is possible during unloading without any time loss.

In these cases the size of the Diesel tanks can be assumed to be large enough despite the significantly lower energy density, which is why the costs for the LOHC tank are neglected.

Cargo vessel

For the cargo vessel defined in the busy route Antwerp-Mainz and retour is considered. Based on the analysis in section 2.4.1, during the upstream voyage of about 50 hours, 25 MWh propulsion energy is needed at the shaft corresponding to an average shaft power of 500 kW, whereas for the 28 hour downstream voyage at an average shaft power of 240 kW an energy of 6720 kWh is necessary.

Table 4.10: Energy consumption and storage size for the cargo vessel

Cargo Vessel		**Upstream**	**Down-stream**	**Roundtrip**
Energy at shaft	kWh	25,000	6720	31,720
Fuel energy	kWh	59,524	16,000	75,5240
Hydrogen mass	kg	1786	480	2266
LH_2 tank volume	m³	46	31	56
LOHC tank volume	m³	38	10	48
40 ft CH_2 storage container	number	1.7	0.5	2.2

The results of the calculation are presented in Table 4.10. The cargo ship needs three containers for the round trip with the possibility to reduce this amount to 2, if at the end of the upstream trip new fuel is bunkered. As more containers allow a more flexible and even further operation, the calculation is continued on with the more conservative estimation of three containers. Relating this number to the ship's capacity of 192 TEU, this corresponds to roughly 3 % of the total cargo capacity. The compressed hydrogen storage system exhibits a volume of 258 m³ and a mass of 28 t. The three compressed hydrogen storage containers would cost approximately 2,700,000 €.

The calculated tank volume for the liquid hydrogen tank and the multi-chamber LOHC tank are 56 m³ and 48 m³, respectively. The liquid hydrogen tank would cost approximately 170,000 €.

To provide the amount hydrogen corresponding to a maximum main engine power of 1300 kW, for dehydrogenation of the LOHC 4.2 40 ft container release units (see Table 4.1) are needed.

Pushed convoy

For the pushed convoy with a maximum propulsion power, during the 26 h upstream voyage 79 % of the maximum power of 3800 kW are demanded on average, whereas 30 % are needed during the 13 h downstream voyage. This results in a liquid hydrogen tank volume of 112 m³. The LH_2 tank would cost approximately 360,000 €.

Alternatively, six and a half 40 ft high cube containers are necessary, as shown in Table 4.11. Regarding the relatively small size of the push boat, this amount (559 m³) might be too large in the concrete case.

Beside an LOHC tank volume of 141 m³, 12 units, each of the size of a 40 ft intermodal container, are needed to provide hydrogen for a maximum engine power of 3800 kW while assuming there is no gaseous hydrogen buffer for serving the peak power demand.

The containers have a total volume of 924 m³ and hence exceed the capacity of the push boat by far.

Table 4.11: Energy consumption and storage size for the pushed convoy

Pushed Convoy		**Upstream**	**Down-stream**	**Roundtrip**
Energy at shaft	kWh	78,000	14,820	92,820
Fuel energy	kWh	185,714	35,286	221,000
Hydrogen mass	kg	5571	1059	6630
LH_2 tank volume	m³	121	38	151
LOHC tank volume	m³	119	23	141
40 ft cH_2 storage container	number	5.5	1,0	6.5

Cabin vessel

Cabin vessels are operated in very different ways and on various routes. Because the load profiles including auxiliary power consumption are not publicly available, for the calculations in this chapter only a very general estimation of the boundary conditions can be made. The exemplary trip of the ship introduced in section 2.4.3 with a maximum propulsion power of 1200 kW consists in total of 48 hours upstream voyage at an average of 70 % of the maximum power, 24 h being docked ashore, and 24 hours downstream voyage at 20 % of the maximum propulsion power. At all times the hotel operation is assumed to require 500 kW electrical energy. The energy consumption for this case is presented in Table 4.12.

Table 4.12: Energy consumption and storage size for the cabin vessel

Cabin vessel		**Upstream**	**Docking**	**Down-stream**	**Roundtrip**
Energy at shaft	kWh	64,320	12,000	17,760	94,080
Fuel energy	kWh	153,143	28,571	42,286	224,000
Hydrogen mass	kg	4594	857	1269	6720
LH_2 tank volume	m³	99	35	42	158
LOHC tank volume	m³	98	18	27	143
40 ft cH_2 storage container	number	4.5	0.8	1.2	6.6

About two thirds of the energy is required for the upstream voyage. For the defined roundtrip a liquid hydrogen tank of 158 m³ is needed, estimated at 370,000 €, or an

LOHC tank of 143 m³, or 7 40 ft high cube compressed hydrogen containers costing about 6.3 million Euros. Additionally to the LOHC tank 9 release units, each in a 40 ft container, are necessary to provide a maximum genset power of 2754 kW making this option rather unattractive. On passenger ships there are only very limited options to install tanks on deck, because these are the preferred spots for passenger use and also installations in these locations might impair the outer appearance of the vessel.

Rhine ferry

For a Rhine ferry with the operating profile specified in section 2.4.4 the energy consumption is determined. Information provided by several ferry operators and on-board analyses revealed an average engine power of 200 kW to 300 kW, depending on the vessel size and local situation. An average daily fuel consumption of 300 l diesel can be considered representative for many of these vessels. This corresponds to 3,000 kWh fuel energy. Assuming the same engine efficiency with hydrogen operation, this is equivalent to 629 kg hydrogen per week.

Table 4.13: Energy consumption and storage size for the Rhine ferry

Rhine ferry		Per four days
Energy at shaft	kWh	8800
Fuel energy	kWh	20,952
Hydrogen mass	kg	629
LH_2 tank volume	m³	31
LOHC tank volume	m³	13
40 ft cH_2 storage container	number	0.6

As shown in Table 4.13, this amount can be stored in 0.6 40 ft high cube containers for compressed hydrogen storage corresponding to a storage system volume of 52 m³. Current ferries of the considered size have tank sizes of maximum ca. 15 m³. By using a larger space below deck and possible further storage capacities on deck and at the same time by reducing the refueling interval to one week, the compressed solution appears feasible for this application.

The LOHC tank volume is about 13 m³. Additionally, one hydrogen release unit installed in a 40 ft container (approx. 77 m³) is required to provide hydrogen for the maximum engine power of 300 kW. The system complexity is a drawback especially if smaller amounts of hydrogen are to be stored.

The liquid hydrogen tank volume is about 31 m³ with a liquid hydrogen content of only 9 m³. When increasing the volume, the surface area increases less than proportionately. Hence, the specific boil-off losses increase, a large fraction of which cannot be used because these ferries normally do not operate at night. This makes this kind of storage undesirable for such a small amount.

Fueling times

Filling one 40 ft HC compressed gaseous hydrogen storage container takes about five hours. In case the piping infrastructure is sufficient, several containers can be filled in parallel. However, exchanging the entire container is the method of choice and significantly faster, but requires the containers to be easily accessible. Nevertheless, this number can serve as basis for the fueling time for the ferry which amounts to about 3 h. As mentioned in section 4.3.3, with ferries fueling time is not critical aspect, as long as it can be guaranteed that normal operation can continue during the fueling process with the fueling truck being on the ferry.

The liquid hydrogen fueling times for the cargo vessel are about 3 h, and 9 h for both the pushed convoy and the cabin vessel. These numbers exclude precooling of the pipes of about one hour and are based on fueling of one 3500 kg liquid hydrogen load (4 h pumping time per load). If two fueling trucks are used in parallel and if both onboard and landside infrastructure are sufficient, this time can be decreased twofold.

For diesel fuel flow rates are between 200 l/min and 900 l/min, depending on the number of hoses (1-2) and the venting capacity of the receiving tank. The flow rate of LOHC is very similar. However, since the energy density of LOHC fuels is about five times lower than that of diesel, so is the fueling time. For comparison, the fueling times for diesel and LOHC are contrasted in Table 4.14 for the considered applications. It should be noted that the duration of bunkering can be decreased significantly by increasing the number of hoses.

Table 4.14: Fueling times for LOHC and Diesel for the selected application cases

Fueling time	**Cargo vessel**	**Pushed convoy**	**Cabin vessel**	**Rhine ferry**
	min	min	min	min
LOHC	53-240	157-705	159-715	14-65
Diesel	10-45	30-133	30-135	3-12

4.5.2 Requirements for each specific type of ship

First, the partners jointly defined a list of criteria relevant for ship operation. Subsequently, these requirements were rated regarding their importance for each specific type of vessel. The results are displayed in Table 4.15. The importance of an aspect from not important at all to very important and is mirrored by the symbols --, -, o, +, ++.

Table 4.15: Rating of requirements to their ship-specific relevance

Operational Aspects	Cargo vessel	Pushed convoy	Cabin vessel	Rhine ferry
Noise/vibration	--	--	++	-
Emissions (exceeding regulation)	--	--	+	o
Range	++	o	-	-
Reliability	+	+	-	++
Easy bunkering	-	+	-	-
Cost per ton (or person) and km	++	++	o	+
Handling (crew competences)	o	-	--	-

For the ships transporting freight the specific costs are the most important criterion, whereas noise, vibrations and emissions exceeding the mandatory regulations do not play a role for these kind of ships. On the other end, cabin vessels operators face many more cost factors than only fuel, such as personnel for the hotel operation, food, etc., so that the pure technical ship operation is not the only determining factor.

Particularly noise and vibrations should only be present to the least possible degree for comfort reasons. For the same reason, emissions should be kept low in order not to impair passenger comfort by soot deposits, but also for public image reasons. For river ferries, this noise, vibrations and emissions are by far less important, because the single ride is very short. However, it is still more important for ferries than for cargo ships, because, still passengers are transported and moreover, the ferries always runs at the same location making it necessary also to be mindful of the surroundings.

The cabin vessel is assumed to have the best trained crew having sufficient competences in handling also complex technologies. Thus, the simplicity of handling is only a minor criterion for this kind of ship. The same, to a limited extent holds true for the ferry and the pushed convoy.

The range is a very important for the cargo vessel that runs long distances and whose earnings have a strong correlation to the travel time which makes extra fuel stops inconvenient. For pushed convoys, time is still an important factor regarding cargo rates, but distances are shorter than for the cargo vessel so that a long range is not considered as important. In Europe, the cabin vessel generally travels shorter distances between the stops offering possibilities for refueling. Ferries do not leave their operating location so that shorter refueling intervals are conceivable.

Easy bunkering plays an important role for the pushed convoy. The concept is that in the ideal case the pusher craft drops off the barges at the destination and is combined with new barges without waiting for the first ones to be unloaded. Thus, time should not be wasted with long bunkering procedures. Cargo vessels that usually bunker during freight loading have more time for these processes.

4.5.3 Features of storage technologies

The assessment of the three storage types most promising on the short term results in the matrix is given in Table 4.16. The extent to which a technology is advantageous regarding the corresponding aspect from fully disadvantageous to highly advantageous is mirrored by the symbols --, -, o, +, ++.

Table 4.16: Analysis of technical features for storage

Operational Aspects	CH_2	LH_2	LOHC
Noise/vibration	++	+	+
Emissions (exceeding regulation)		n/a	
Range	-	+	+
Reliability	++	o	-
Easy bunkering	+	o	++
Cost per ton (or person) and km	+	o	-
Handling (crew competences)	+	o	-

Compressed hydrogen storage systems only consist of the hydrogen tanks and pressure regulation valves and hence are no cause for noise or vibrations. The more complex liquid hydrogen storage and LOHC storage systems include a vaporizer and releaser unit, respectively, whose components such as pumps could cause noise and vibrations.

The range of the ship is proportionate to its stored hydrogen mass which in turn is – besides weight restrictions – mainly limited by the available space. This favors liquid hydrogen and LOHC storage systems compared to storage of compressed gas.

The complexity of the former decreases the system liability and demands a trained crew compared to the latter. Bunkering is considered easiest for LOHC as the existent diesel infrastructure and procedures could be used. Handling gaseous hydrogen is by far less complicated than handling liquid hydrogen at extremely low temperatures.

4.5.4 Features of energy converter technologies

Analogously to the storage technologies, the features of the energy converter technologies are translated to the matrix structure as well (see Table 4.17). The scale is the same as for the storage technologies. Fuel cell systems tend to be quieter than internal combustion engines and cause significantly less vibrations. On the other hand combustion engines are established and refined products offering a high level of reliability. Their production costs are substantially lower than those of fuel cells. Due to the lower technology readiness level of fuel cells and their limited durability, the costs for components replacement are expected to be higher with the fuel cell technology. It should be noted that with increasing technology readiness level both costs will decrease and reliability will increase. Nowadays fuel cells are very sensitive, whereas combustion engines are a very robust product. Furthermore, the personnel working in the shipping sector is familiar with combustion engine operation. The newer and the more complex the system, the more highly trained the crew must be.

Table 4.17: Analysis of technical features for converters

Operational Aspects	ICE	ICE genset	LT-PEM	HT-PEM	SOFC
Noise/vibration	--	-	++	+	+
Emissions (exceeding regulation)	--	--	++	++	++
Range			n/a		
Reliability	++	+	o	--	-
Easy bunkering			n/a		
Cost per ton (or person) and km	++	+	-	-	-
Handling (crew competences)	++	+	-	-	-

4.5.5 Combinations of storage and converter technologies

Last, the energy storage technologies are assessed how well they can be combined with the energy conversion technologies (see Table 4.18). Compressed gaseous hydrogen is advantageous in that no compression to the required inlet pressure of the converter is necessary. Combustion engines can profit from this circumstance in particular because the necessary pressures are higher than with fuel cells.

To dehydrate the LOHC, heat at temperatures beyond 200 °C is needed. This cannot be provided by PEM fuel cells. Unless other waste heat sources are available, LOHC storages cannot be combined with PEM fuel cells, because generating heat only for this purpose is highly inefficient, as stated before. The temperature level of combustion engines and SOFCs, however, is sufficient. As SOFCs are operated stationary, they are less affected by the inertia of the releaser units than converters operated more dynamically.

Liquid hydrogen also must be evaporated by heat input, but the amounts are significantly lower so that the above effects still apply, but to a mitigated extent.

Table 4.18: Evaluation of storage and converter combinations

Technology Combination	cH_2	LH_2	LOHC
ICE	++	+	+
ICE genset	++	+	+
LT PEM	+	o	--
HT PEM	+	o	--
SOFC	+	++	++

4.5.6 Matrix combination and case evaluation

In a final step, the symbols in the matrices are translated into numbers by the following weighting: From - - to ++ each symbol is allocated a whole number between 1 and 5. This quantification of the previously qualitative analysis is no definite step, but is as subjective as the qualitative analyses themselves. Separately for each type of ship, the number representing the importance of each aspect is multiplied by the number describing the advantageousness of each technical solution. Then the products, as the weighted performance of the technology regarding the specific aspect and type of ship, are summed up for each technology. This leads to the matrices shown in Table 4.19 and

Table 4.20. As the results are quite distinct and so are the possible combinations according to Table 4.18, the technology combination matrix need not be included in the final evaluation.

Table 4.19: Ship-specific suitability of energy conversion technologies

	ICE	ICE genset	LT-PEM	HT-PEM	SOFC
Cargo vessel	62	51	38	29	33
Pushed convoy	57	47	36	27	31
Cabin vessel	39	38	59	50	52
Rhine ferry	70	59	56	44	49

Table 4.20: Ship-specific suitability of energy storage technologies

	cH_2	LH_2	LOHC
Cargo vessel	75	66	58
Pushed convoy	75	61	58
Cabin vessel	63	52	80
Rhine ferry	91	70	67

Regarding the comparison of the storage technologies it is salient that compressed gaseous hydrogen is dominant for every type of vessel. This is because compressed hydrogen performs better than liquid hydrogen and LOHC storages in every category apart from range whilst range being an aspect of only minor importance except for with the cargo vessel. For the pushed convoy, however, prior to this analysis compressed hydrogen was excluded as storage because of its size and the lack of space onboard this type of ship. LOHC was excluded because of the size of the necessary releaser units.

As to the energy conversion technologies, according to this analysis the internal combustion engine is favored for all considered ships except for the cabin vessel. The reason for this is that costs are very important for these ships – an aspect that fuel cells currently only achieve poor results in. Emissions, however, are of only little importance so that the benefits of fuel cells are not demanded in these application cases. The situation is different for the cabin vessel whose requirements are contrary: whereas costs are not as important, the absence of noise and emissions is crucial. This analysis outputs the LT-PEM fuel cell as the most favorable energy converter.

Though, it must be pointed out that these results are closely related to the chosen weighting. For a different weighting the results might not be the same. Moreover, this analysis is based on the current situation. If requirements shift, for instance based on tightened regulatory noise or emission limits, different technologies will be favored. This is also the case for a change in technical features. The further technological development of the fuel cell technology and the transition from manual assembly to larger scale automatized production will lead to an increase in reliability, durability and a cost reduction.

Consistent with the matrix analysis and preceding exclusions, the direct drive internal combustion engine in combination with a liquid hydrogen storage is the most favorable solution for the pushed convoy.

Nevertheless, beside the recommendations of the matrix analysis also other configurations are worth considering. For the cargo vessel a compressed hydrogen storage and an internal combustion engine genset and electric propulsion motor combination is promising. In contrast to the rather steady load profile of a pushed convoy, it varies for the exemplary cargo vessel that runs on major as well as tributary rivers and canals so that the full potential of running the combustion engines in the optimal operation point independent of the driving situation can be used.

The Rhine ferry could be equipped with a compressed hydrogen storage and an LT-PEM fuel cell that harmonizes well with the often prevalent part load operation of the ferry.

Last, the cabin vessel could be operated with an SOFC and a liquid hydrogen storage. The high auxiliary power consumption allows for less dynamic operation of the system so that one major disadvantage of this technology can be compensated for. The waste heat at high temperature can be used for dehydrogenation or vaporization and the hotel operation.

It must be kept in mind that the presented results are valid under very specific boundary conditions and that other configurations should be considered as well.

5 Legal Frame Conditions

In this chapter the legal framework regarding the general installation of fuel cells and hydrogen tanks on board is focused on. This chapter begins with a short review of emission standards for IWT in section 5.1. In sections 5.2 and 5.3, rules for the use of fuel cells in shipping and in general are presented, respectively. This is followed by the rules for hydrogen storage and bunkering in sections 5.4 and 5.5, respectively. Based on the previous analyses, the blank gaps are summarized in section 5.6.

5.1 Emission regulations

The emission regulations for IWT are the CCNR stages I and II and the newly released EU Regulation 2016/1628 on "‘Requirements relating to gaseous and particulate pollutant emission limits and type approval for internal combustion engines for non-road mobile machinery"’. This new EU-regulation amends the former versions (EU) No 1024/2012 and (EU) No 167/2013, and amends and repeals Directive 97/68/EC. Table 5.1, Table 5.2 and Table 5.3 show the respective limit values for emissions.

Table 5.1: CCNR Stage I (Directive 97/68/EC)

Emission Stage	Power Range	CO	HC	NO_x	PM mass
	kW	g/kWh	g/kWh	g/kWh	g/kWh
Stage I	37 ≤ *P* < 75	6.50	1.30	9.2	0.85
Stage I	75 ≤ *P* < 130	5.00	1.30	9.2	0.7
Stage I	*P* > 130 and 500 1/min < n < 2800 1/min	5.00	1.30	$45 \cdot n^{(-0.2)}$	0.54
Stage I	*P* > 130 and *n* > 2800 1/min	5.00	1.30	9.2	0.54

The values for CCNR Stage I [EPC98] and CCNR Stage II [EPC04] are measured with the test cycle ISO 8178-4, E2/E3/D2/C1.

Table 5.2: CCNR Stage II (Directive 2004/26/EG)

Emission stage	Power range	CO	HC	NO_x	PM mass
	kW	g/kWh	g/kWh	g/kWh	g/kWh
Stage II	$18 \leq P < 37$	5.50	1.30	9.2	0.85
Stage II	$37 \leq P < 75$	5.00	1.30	9.2	0.7
Stage II	$75 \leq P < 130$	5.00	1.30	$45 \cdot n^{(-0.2)}$	0.54
Stage II	$130 \leq P < 560$	3.50	1.30	9.2	0.54
Stage II	$P > 560$ and $n < 3430$ 1/min	3.50	1.30	$45 \cdot n^{(-0.2)}$	0.54
Stage II	$P > 560$ and $343 \leq n < 3150$ 1/min	3.50	1.30	$45 \cdot n^{(-0.2)}$	0.54
Stage II	$P > 560$ and $n \geq 3150$ 1/min	3.50	1.30	$45 \cdot n^{(-0.2)}$	0.54

Table 5.3: Regulation (EU) 2016/1628 of the European Parliament

Emission stage	**Engine sub-category**	**Power range**	**Ignition type**	**CO**	**HC**	**NO_x**	**PM mass**	**PN**	**A**
		kW	-	g/kWh	g/kWh	g/kWh	g/kWh	#/kWh	
Stage V	IWP-v-1, IWP-c-1	$19 \leq P < 75$	all	5.0	$HC + NO_x \leq 4.70$		0.30		6.0
Stage V	IWP-v-2, IWP-c-2	$75 \leq P < 130$	all	5.0	$HC + NO_x \leq 4.70$		0.14	-	6.0
Stage V	IWP-v-3, IWP-c-3	$130 \leq P < 300$	all	3.5	1.00	2.10	0.10	-	6.0
Stage V	IWP-v-4, IWP-c-4	$300 \geq P$	all	3.5	0.19	1.80	0.02	10^{12}	6.0

It can be seen that the emission regulations for IWT were tightened over the years. The token for the IWT engines is IWP. In the new regulation 2016/1628 the engines are divided into eight categories, depending on their speed operation and power range. The categories can be seen in Table 5.4

Table 5.4: Sub-categories of engine category IWP

Category	Ignition type	Speed operation	Power range / kW	Sub-category	Reference power
IWP	all	variable	$19 \leq P < 75$	IWP-v-1	Maximum net power
			$75 \leq P < 130$	IWP-v-2	
			$130 \leq P < 300$	IWP-v-3	
			$P \geq 300$	IWP-v-4	
IWP	all	constant	$19 \leq P < 75$	IWP-c-1	Rated net power
			$75 \leq P < 130$	IWP-c-2	
			$130 \leq P < 300$	IWP-c-3	
			$P \geq 300$	IWP-c-4	

The values for 2016/1628, Stage V, are measured with the test cycle ISO 8178-4, E2 and E3 [IOS17].

Table 5.5: Dates of application of Regulation (EU) 2016/1628 for engine category IWP

Category	Ignition type	Power range (kW)	Sub-category	Mandatory date of application of this regulation for	
				EU type-approval of engines	Placing on the market of engines
IWP	all	$19 \leq P < 130$	IWP-v-1 IWP-v-2 IWP-v-3 IWP-c-1 IWP-c-2 IWP-c-3	1 January 2018	1 January 2019
		$P \geq 300$	IWP-v-4 IWP-c-4	1 January 2019	1 January 2020

Table 5.6: Non-road steady-state test cycles (NRSC) for engines of category IWP

Category	Speed operation	Purpose	Sub-category	Test cycle (ISO 8178:4-2017)
IWP	variable	Variable-speed engine intended for propulsion that operates on a fixed-pitch propeller curve	IWP-v-1 IWP-v-2 IWP-v-3 IWP-v-4	E3
	constant	Constant-speed engine intended for propulsion that operates with a controllable pitch or electrically coupled propeller	IWP-c-1 IWP-c-2 IWP-c-3 IWP-c-4	E2

5.2 Rules for fuel cells in shipping

The EMSA study on the use of fuel cells in shipping gives a good overview of the classification rules applicable for fuel cell installation [Tro17]. The overview concentrates on seagoing ships, nonetheless, most of the topics here might be used as blueprint for IWT.

In Table 5.7 and Table 5.8 the relevant class rules of the largest European classification societies and an overview of applicable class rules and key features are given.

Table 5.7: Overview of applicable class rules for fuel cell installations and their status [Tro17]

Association	Title of document	Status
Det Norske Veritas (DNV)	DNV Rules for Classification: Part 6-Chapter 23: Fuel Cell Installations	Released July 2008 (expired)
Germanischer Lloyd (GL)	GL Klassifikationsvorschriften: VI-Teil 3-Kapitel 11: Richtlinien fur den Einsatz von Brennstoffzellen-System an Bord von Wasserfahrzeugen	Released 2002 (expired)
Lloyds Register (LR)	LR Technical Papers: Development of requirements for Fuel cells in the marine environment – Performance and prescription	Released 2006
Bureau Veritas (BV)	Guidelines for Fuel cell Systems On-board Commercial Ships	Released April 2009
DNV GL	DNV GL rules for classification of Ships: Part 6 Ch. 2 Sec.3: Fuel cell Installation - FC	Released January 2016

Table 5.8: Overview of applicable class rules and key features; adapted from [Tro17]

	BV	DNV GL	LR
Own prescriptive rules	Directive published in 2009	Directive published in 2016	-
Alternative authorization procedure	-	-	Risk-based process
Based on MSC.285(86) (LNG interim guidelines)	Yes	Yes	No
Regulated fuels	Natural gas, hydrogen	All fuels with flashpoint ≤ 60°C	No; Risk-based process
Class approval mark	No	FC(Power), FC(Safety)	No
Risk analysts required	Yes, No specific method	Yes, FMEA	Yes, No specific method
Complementary material requirements	Yes, Hydrogen (gaseous, liquefied)	Reference to general guidelines of DNV GL	No

5.3 General international standards for fuel cells

Furthermore, the EMSA study gives an overview of international standards for FCs like those of the International Electrotechnical Commission IEC and the International Organization of Standardization ISO. The most important standards are:

“IEC 62282-1:2012 Terminology

The first part of the standard series provides uniform terminology in the forms of diagrams, definitions and equations related to fuel cell technologies in all applications.

IEC 62282-2:2012 Fuel cell modules

This part provides the minimum requirements for safety and performance of fuel cell modules with or without an enclosure which can be operated at significant pressurization levels or close to ambient pressure. It applies to fuel cell modules with any kind of electrolyte chemistry.

IEC 62282-3-100:2012 Stationary fuel cell power systems - Safety

This standard is applicable to stationary fuel cell power systems intended for indoor and outdoor commercial, industrial and residential use in non-hazardous areas, with or without the ability to recover useful heat. It applies to all kind of fuels like natural gas and other methane rich gases, fuels from oil refining, liquids and hydrogen rich gaseous. Although this part does not cover propulsion fuel cell power systems, it is applicable to marine auxiliary power systems.

IEC 62282-3-200:2015 Stationary fuel cell power systems - Performance test methods

This part covers operational and environmental aspects of the stationary fuel cell power systems performance for systems with an electrical output of over 10 kW (systems with less than 10kW are dealt with IEC 62282-3-201).

IEC 62282-3-300:2012 Stationary fuel cell power systems - Installations

This part provides minimum safety requirements for the installation of indoor and outdoor stationary fuel cell power systems in compliance with IEC 62282-3- 100.

IEC 62282-7-1:2010 Single cell test methods for polymer electrolyte fuel cell (PEFC)

This Technical Specification describes standard single-cell test methods for polymer electrolyte fuel cells (PEFCs). It provides consistent and repeatable methods to test the performance of single cells and cell components, including membrane-electrode assemblies (MEAs) and flow plates. This Technical Specification is also available for fuel suppliers to determine the maximum allowable impurities in fuels.

IEC 62282-7-2:2014 Single cell and stack performance tests for solid oxide fuel cells (SOFC)

This standard describes test methods for a single cell and stack that is to be employed in power generation systems using solid oxide fuel cells (SOFCs), but is not applicable to small button cells that are designed for SOFC material testing and provide no practical means of fuel utilization measurement. It is to be used for data exchanges in commercial transactions between cell manufacturers and system developers.

ISO 14687-3:2014 Proton exchange membrane (PEM) fuel cell applications for stationary appliances

The purpose of this part is to establish an international standard of quality characteristics of hydrogen fuel for stationary fuel cells.

ISO 16110-1:2007 Hydrogen generators using fuel processing technologies – Safety

Part 1 of this standard applies to packaged, self-contained or factory matched hydrogen generation systems with a capacity of less than 400 m³/h at 0 °C and 101.325 kPa, intended for indoor and outdoor commercial, industrial, light industrial and residential use. It applies to hydrogen generators using one or a combination of different fuels like natural gas and other methane-rich gases, fuels derived from oil refining, fossil fuel sources (e.g. methanol) and gaseous mixtures containing hydrogen gas. Hydrogen generators are referred to as devices that convert a fuel to a hydrogen-rich stream of composition and conditions suitable for the type of device using the hydrogen. This device can be a fuel cell power system, or a hydrogen compression, storage and delivery system. It aims to cover all significant hazards, hazardous situations and events relevant to hydrogen generators, with the exception of those associated with environmental compatibility.

[…] Since 2008 fuel cells for maritime and other purposes in Germany have been certified according to DIN EN 62282-2 which is based on the IEC 62282-2 standard. Furthermore, the existing class guidelines for fuel cell installations on ships of the DNV GL and of other classes contain references to the IEC standards and recommend test procedures (manufacturer and sea trial) based on these standards. The IEC is currently working on the extension of 62282-3-400, to regulate small stationary fuel cell power system with combined heat and power output and on 62282-8, to regulate Energy storage systems using fuel cell modules in reverse mode (coming into force 2019).” [Tro17]

5.4 Standards for hydrogen storage

The EMSA study also gives an overview of the standards for the storage of hydrogen [Tro17]:

“ISOTR15916 Basis considerations for the safety of hydrogen systems

ISOTR15916 gives a very useful overview of safety relevant properties and related considerations for hydrogen. Annex C gives a good and very relevant overview of low temperature effects of hydrogen on materials, and the document also suggest suitable material selection criteria including how to consider hydrogen embrittlement.

Compressed gas hydrogen storage

European standards covering pressure vessels used for pressures exceeding 0.5 bar are harmonized with PED. EN 1252-1:1998 on storage tank materials, EN 1797:2001 on gas/material compatibility, and EN 13648 part 1, 2, and 3 on safety devices for protection against excessive pressure are some of the standards related to hydrogen storage.

ISO 15399 Gaseous Hydrogen - Cylinders and tubes for stationary storage.

This standard covers cylinders and tubes intended for the stationary storage of gaseous hydrogen of up to a volume of 10 000 l and a pressure of 110 MPa, of seamless metallic or composite construction. The EIGA code of practice IGC 15/06 covers storage of gaseous hydrogen. IGC 15/06 on gaseous hydrogen, compression, purification, and filling into containers and storage installations at consumer site shall serve as a guide for designers and operators of gaseous hydrogen stations and reflect the best practices currently available. It includes issues such as safety of personnel, operations instructions, protection, and emergency situations. [...]

Liquid hydrogen storage IGF Code/IGC Code

The IGC and IGF codes cover storage of liquefied gas on-board ships. The defined C-tank rules for storage of liquefied gas will in principle cover hydrogen cooled to liquefied form. Additional considerations will however be required due to the properties of hydrogen including the low storage temperatures.

ISO/TC 220

This is a standard for Cryogenic vessels developed for land based application. Set of standards in the field of insulated vessels (vacuum or non-vacuum) for the storage and the transport of refrigerated liquefied gases of class 2 of "Recommendations on the Transport of Dangerous Goods - Model regulations - of the United Nations", in particular concerning the design of the vessels and their safety accessories, gas / materials compatibility, insulation performance, the operational requirements of the equipment and accessories.

Detection of leaks

ISO 26142:2010 Hydrogen detection apparatus - Stationary applications. This standard defines the performance requirements and test methods of hydrogen detection apparatus that measure and monitor hydrogen concentrations in stationary applications. The standard cover hydrogen detection apparatus used to achieve the single and/or multi-level safety operations, such as nitrogen purging or ventilation and/or system shut-off corresponding to the hydrogen concentration. The requirements applicable to the overall safety system and the installation requirements are excluded. This standard sets out only the requirements applicable to a product standard for hydrogen detection apparatus, such as precision, response time, stability, measuring range, and selectivity and poisoning. This standard is intended to be used for certification purposes.

Hydrogen piping network

The standard ISO 15649:2001 on piping for petroleum and natural gas industries is used as a guideline also for hydrogen technologies. This standard is applicable to piping within facilities and for packaged equipment, with exclusion of transportation pipelines and associated plant. The standard EN 13480:2002 is divided in 7 parts specifying the requirements for industrial piping systems and supports made of metallic materials." [Tro17]

5.5 Standards for hydrogen bunkering

In the International Code of Safety for Ship Using Gases or other Low-flashpoint fuels (IGF-Code) hydrogen is not listed as fuel [IMO17]. The EMSA study [Tro17] suggests to establish a guideline for the bunkering of all low-flashpoint, cryogenic substances and refers to the procedure for LNG:

"Some available regulative documents support bunkering of LNG, notably the ISO/TS 18683 - Guidelines for systems and installations for supply of LNG as fuel to ships, issued Jan 2015. ISO TS 18683 was developed to clarify the aspects of bunkering of LNG fuel in a port environment. The standard gives guidance on the minimum requirements for the design and operation of the LNG bunkering facility, including the interface between the LNG supply facilities and receiving ship. The standard provides requirements and recommendations for operator and crew competency training, for the roles and responsibilities of the ship crew and bunkering personnel during LNG bunkering operations, and the functional requirements for equipment necessary to ensure safe LNG bunkering operations of LNG fueled ships. The standard is applicable to bunkering of both seagoing and inland trading vessels. It covers LNG bunkering from shore or ship LNG supply facilities, and addresses operations required such as inerting, cooling down, and loading.

The standard ISO 20519 "Ships and marine technology - Specification for bunkering of gas fueled ships" is under preparation for its final publication. This standard will cover aspects as vessel and transfer system design requirements, emergency release system (breakaway) and emergency shut-down system, hoses, bunkering connections. Although it is a standard for gas fueled ships, the standard appears to focus on LNG.

Over the last years, several guidelines designed to handle LNG bunkering have been published. [...]

- IACS LNG bunkering Guidelines (No 142)9 was published in June 2016. The document provides recommendations for the responsibilities, procedures and equipment required for LNG bunkering operations and sets harmonized minimum baseline recommendations for bunkering risk assessment, equipment and operations.

- The Society for Gas as a Marine Fuel (SGMF) has released the "LNG Bunkering - Safety Guidelines" (Feb 2015). The document includes chapters on LNG hazards, safety systems, bunkering and specific safety guidance for ship to ship, shore to ship and truck to ship bunkering.
- The International Association of Ports and Harbors (IAPH) issued check lists for LNG bunkering.
- Bureaus Veritas (BV) has also released LNG Bunkering Guidelines.

In Norway, bunkering of LNG to passenger vessels is subject to approval from the Norwegian Directorate for Civil Protection independent on whether the bunkering is from a permanent facility of from a truck. Requirements have not yet been developed for bunkering of hydrogen or other gaseous low flashpoint fuels as fuel in maritime applications. Liquid hydrogen is commercially available on trucks hence the current practices applied for hydrogen being transported as cargo should be consulted. At the MSC 96 in May 2016, an agreement was made to invite ISO to develop a standard LNG bunkering safety checklist. [...]

The land side part of the bunkering operation is not part of the IGF-Code. Therefore, other standards for safe bunkering of the relevant fuels are needed to support the implementation of bunkering technology for maritime use. The ships side of the bunkering operation (from the bunkering flange on the ship side) is covered by the IGF-Code. For bunkering of compressed hydrogen gas, experience and standards used in land based applications will be relevant. A starting point will be the currently available systems for filling of hydrogen on hydrogen cars, trucks and buses. Upscaling issues will need to be addressed, considering the temperature requirements for safe hydrogen refueling as too high temperatures in the receiving tanks must be avoided. SAE J2601 is an industry standard on the protocol for fueling road vehicles developed by SAE (Society of Automotive Engineers). It gives tables of ramp up rate of the tank pressure during fuel transfer but its target is limited to transfers of relatively small amounts. It appears to be the only published fueling protocol for fueling of hydrogen vehicles up to 700 bar tanks. The SAE J2602 will be a good starting point, but current ongoing standardization initiatives should also be consulted.

Other relevant standards are:

ISO 17268:2012 Gaseous hydrogen land vehicle refueling connection devices

This standard defines the design, safety and operation characteristics of gaseous hydrogen land vehicle (GHLV) refueling connectors consisting of, as applicable, a receptacle and a protective cap (mounted on vehicle), and a nozzle. It applies to refueling connectors which have working pressures of 110 bar, 250 bar, 350 bar and 700 bar.

ISO/TS 19880-1:2016 Gaseous hydrogen- Fueling stations - Part 1: General requirements

This standard recommends the minimum design characteristics for safety and, where appropriate, for performance of public and non-public fueling stations that dispense gaseous hydrogen to light duty land vehicles (e.g. Fuel cell Electric Vehicles). The recommendations are in addition to applicable national regulations and codes, which can prohibit certain aspects of this standard. ISO/TS 19880 is applicable to fueling for light duty hydrogen land vehicles, but it can also be used as guidance for fueling buses, trams, motorcycles and fork-lift truck applications, with hydrogen storage capacities outside of current published fueling protocol standards, such as SAE J2601. It provides guidance on elements of a fueling station as hydrogen production/delivery system, delivery of hydrogen by pipeline, liquid hydrogen storage, hydrogen purification systems, as applicable and gaseous hydrogen dispensers.“ [17]

Useful information for both storage and bunkering might also be provided by ISO/TS 16901 from 2013 which is a guidance on performing risk assessment in the design of onshore LNG installations including the ship/shore interface, by DNVGL-RP-G105 from 2015, “Development and operation of liquefied natural gas bunkering facilities” as well as the ABS documents “LNG Bunkering: Technical and Operational Advisory” and “Bunkering of Liquefied Natural Gas-fueled Marine Vessels in North America”.

5.6 Identified gaps

Regarding the use of hydrogen as fuel on inland waterway vessels, some regulatory gaps in the categories "Hydrogen as Fuel", "Bunkering", "Storage on Board" and "Fuel Cell System" could be identified. The gaps are classified as legal or knowledge gaps.

Table 5.9: Regulatory Gaps; partly adapted from [Tro17]

Gap	Recommendation	Type
Hydrogen as Fuel		
ADN	In the ADN fuel cells are listed under UN 3166 and are exempted from the rules: “The provisions laid down in the ADN do not apply to electric energy storage and production systems (e.g. lithium batteries, electric capacitors, asymmetric capacitors, metal hydride storage systems and fuel cells): - installed in a means of transport, performing a transport operation and destined for its propulsion or for the operation of any of its equipment - contained in an equipment for the operation of this equipment used or intended for use during carriage (e.g. a laptop computer)”	legal
IGF Code	Hydrogen as fuel is not included in the IGF Code	legal
Bunkering		
Harmonized rules for bunkering of low-flashpoint fuels	Development of standardized bunkering procedures for both ship and shore. Carried out risk studies and collected practical information	legal, knowledge
Storage on Board		
Storage of gaseous hydrogen	Qualification of pressure tanks for maritime use with compressed hydrogen gas. Safety studies considering hydrogen pressure tanks and requirements for safe solutions. Development of provisions for possible high-pressure storage technologies in enclosed areas.[Tro17]	legal, knowledge
Storage of gaseous hydrogen	Possible storage related failure modes need to be understood, and land based solutions adjusted if necessary for safe application. [Tro17]	legal, knowledge
Fuel Cell System		
Handling	Development of general procedures for safe handling and management of emergence situations	knowledge
Piping System	Standards for the layout and installation of high pressure hydrogen or low temperature hydrogen piping systems and safety systems	legal, knowledge
Ventilation	Development of standards for the ventilation of enclosed spaces with hydrogen applications. Risk studies and the collection of practical experience.	legal, knowledge
Integration in ship	Definition of EX-Zones etc. related to hydrogen, related risk studies	legal, knowledge

6 Instruction and Training

In this chapter, the special requirements regarding instruction and training of personnel working with hydrogen are outlined.

6.1 Present state: Use of hydrogen for energy generation in shipping

Hydrogen as an energy carrier has great potential for low-emission, environmentally friendly (CO_2-free) ship propulsion systems for inland and sea vessels. In this context, inland waterway propulsion systems are of particular importance, as inland waterway transport (compared to sea transport) is subject to very strict exhaust emission regulations and is in direct competition with land-based transport (rail and truck). Low-emission drive concepts already exist for these land-based transports (e.g. electrified platforms as well as various solutions for low-emission trucks, the first hydrogen-powered buses and cars are currently being tested). Further arguments for the use of hydrogen as fuel for inland waterway shipping are the manageable energy requirements of these calls and the possibility of building up a relatively simple hydrogen bunker infrastructure along the shipping routes. This limits the size of the hydrogen tanks required on board the ships.

Today, molecular hydrogen plays no role as a fuel for both inland navigation and maritime shipping. One exception are conventionally powered submarines with a so-called air independent propulsion (AIP) component from German production (e.g. submarines of class U212a of the German Navy). These submarines store hydrogen (physically attached) in metal hydride storage tanks outside the pressure hull and use the hydrogen together with liquid stored oxygen in fuel cells (total power of the cells approx. 300 kWe). The technical requirements of these systems are very high and cost-intensive due to military requirements.

The use of hydrogen as an energy carrier for ship propulsion can be technically implemented in various ways. In particular, there are different technologies for hydrogen storage (pressure storage, liquefied gas storage, physical/chemical deposits) and for energy conversion (e.g. fuel cells or petrol engines, see the previous chapters of this study). There is no functional infrastructure to store and refuel ships in inland and sea harbors.

Hydrogen also plays no role today as cargo for shipping (=> hydrogen tanker). Today there are no tankers (sea/inland) for the transport of molecular hydrogen (gaseous or liquid). There is currently no significant infrastructure for hydrogen loading and unloading in sea or inland ports. The International Maritime Organiziation (IMO) Regulations: International Code for Ships using Gases and other Low Flashpoint Fuels (IGF Code, 01 / 2017) contains no statements about the use of hydrogen on seagoing ships.

In the 1980´s there were various projects for transporting large quantities of hydrogen by ship. During this time, the renewable energy sources should be used for electrolysis of water to hydrogen in Canada, for example. The hydrogen was to be brought to Europe in a project of Thyssen Nordseewerke, Emden with large sea barges. These projects were not realized.

It follows: There are no explicit regulations or training concepts for the handling of hydrogen as cargo or fuel of ocean-going or inland waterway vessels.

6.2 Recording and requirements of existing education and training programs

The present study mainly deals with the use of hydrogen on seagoing and inland waterway vessels. As already explained, there are no homogeneous training concepts for these application scenarios today.

In the development of training concepts for the use of hydrogen on seagoing or inland waterway vessels, the following existing training areas from related areas can theoretically be used:

- Use of hydrogen as fuel for trucks and cars
- Use of hydrogen in the chemical industry
- Training contents of the German Armed Forces/German Navy for the operation of the U212a submarine (or information from ThyssenKrupp Marine Systems shipyard (HDW, Kiel))
- Experience with the use of natural gas/ LNG on board ships

Providers of training/publications with the general topic: Use of hydrogen are e.g.:

- TÜV Süd
- Centre for further education for innovative energy technologies of the Chamber of Crafts Ulm (WBZU)
- TAK Akademie Deutsches Kraftfahrzeuggewerbe
- European Commission: CORDIS : HYFACT: Training on the safe use of hydrogen

There are several publications on hydrogen use. e.g.:

- BG Bahnen: Hydrogen safety in workshops (10/2009)
- Shell Hydrogen Study (Hamburg 2017)
- Various Linde Group publications

6.3 Development of training concepts with regard to individual aspects

In the context of the use of hydrogen as an energy source for sea and inland waterway vessels (focus on inland navigation), different groups of people with different training needs arise.

- Ship crews: Ship management, machinery personnel, deck personnel
- Shipping company employees (technical inspection, crewing, cargo planning)
- Port personnel (port captains, technical personnel, security personnel, etc.)
- Port fire brigades, water police, pilots

Targeted training concepts are necessary for a safe and effective use of these new technologies with the different activity profiles of the individual groups. These concepts must be based on different training modules that can be individually configured for the individual groups of people.

The trainings must contain theoretical and practical parts (trainings). The training concept must be divided into different training methods:

- Courses (in class form and/or e-learning modules) to impart the theoretical knowledge
- Training with simulation programs (imparting practical knowledge for the safe handling of hydrogen systems)
- Trainings / demonstrations in a real hydrogen facility (to deepen/ consolidate the practical knowledge already acquired)

In doing so, account must be taken of the different educational levels and the very different educational levels of the groups of people involved. The training concept should consist of the following modules:

Hydrogen as an environmentally friendly fuel

- Theoretical fundamentals
  - Physical basics
  - Chemical Basics
- Properties of hydrogen in comparison with other fuels
- Origin, transport, storage, implementation
- Economic aspects of hydrogen use

Technology used in the use of hydrogen on ships (according to the solutions proposed in the previous chapters)

- (Combustion) Engines
- Fuel cells
- Components of the hydrogen systems used
  - Pipelines/ fittings,
  - Control and safety systems
  - Tank technologies incl. pressure vessel regulation

- Bunker facilities

Operation of ships / ship installations with hydrogen as fuel

- Safe handling of hydrogen plants / occupational safety
- Visual, functional and leak tests
- Bunkering
- Maintenance /Maintenance
- Accident prevention/behavior in the event of an accident
- Effects of hydrogen propulsion systems on maneuverability
- of ships (dynamics of propulsion, power reserves, ...)

Safe handling of hydrogen / potential hazards

- Safety aspects when handling hydrogen
  - Deep cold hydrogen
  - Hydrogen at high pressure
  - Risk of explosion if hydrogen is mixed with oxygen
- Safety aspects for hydrogen storage
- Safety aspects for the bunkering of hydrogen
- Safety aspects in handling hydrogen propulsion systems on ships
  - Behavior in engine rooms with H2 systems
  - Behavior during repair and maintenance work on H2 systems
  - Behavior in case of fire on board
  - Behavior in the event of an accident

Legal basis for dealing with hydrogen

- General rules
- General requirements for seagoing and inland waterway vessels (not yet defined)
- Special rules and regulations (separate rules for ports and industrial facilities) (not yet defined)

6.4 Development of a new combined training and education concept

The existent training concepts for staff in contact with hydrogen are not suitable for the special needs of the inland water vessel propulsion systems. Onshore and offshore aspects have to be part of the training concept. Today most of the education and training concepts are based on various onshore applications.

According to the different needs of the program participants individual concepts to train these people effectively have to be developed. The modular learning tool system ("box of bricks") as discussed in chapter 6.3 is helpful to combine the various learning aspects into an individual training and education concept.

The learning level has to be adapted to the educational level of the participants. The successful attendance shall be confirmed on an established certificate.

6.5 Development of a possible training schedule

The modular structure of the training concept allows individual adaptation of the training courses for the individual occupational groups. The contents of the individual modules ("depth"/complexity - theory and practice) must also be individually adapted.

This will vary the duration of the training. A reliable statement on the structure of a training schedule is only possible after the results from the other work phases of this study have been presented and the necessary learning content has been detailed.

7 Summary

After emission limits for particulates, CO, HC and NO_x, for instance, have been tightened in the last years, this trend is expected to continue. In order to comply with the new standards, alternative propulsions systems as well as fuels should be considered. From this point of view, hydrogen is very promising, because it allows for reducing emissions significantly.

Hydrogen can be produced on a variety of paths. Nowadays the vast majority originates from reformation of fossil energy carriers, whereas only 4 % comes from electrolysis. Only when produced from renewable energy sources, it can play to its strengths regarding both the use of primary energy and the CO_2 emissions. Furthermore, hydrogen production by means of electrolysis can offer benefits to grid stability and facilitate the efficient use of renewable power plants by the so-called sector coupling. While the increasing number of Power-to-X plants reveal the trend towards “green hydrogen”, during the transition period conventional hydrogen can still serve as adequate fuel to promote hydrogen technologies.

The tight ties between chemical industry and hydrogen as well as between the chemical industry and waterways lead to availability of hydrogen along the main shipping routes. The expected growth of the hydrogen sector including the growing network of gas stations will further guarantee hydrogen availability across Europe. Against the background that additional long-distance road transport would not be accepted to distribute hydrogen to the consumers, electrolysis facilitates a decentralized hydrogen production. Furthermore, existent hydrogen pipeline networks like in the Rhine-Ruhr area and the Netherlands, Belgium and France can be used.

In the harbor, the hydrogen should preferably be stored in the form it is delivered from the producer and provided to the consumer. Due to additional energy losses, conversion between the various forms of storage should be strictly avoided. The conventional ways of bunkering, namely by bunker boat, truck or pipeline can also be applied with hydrogen.

Hydrogen can be stored in various ways: for example in compressed or liquid form, in liquid organic hydrogen carriers (LOHC) or metal hydrides. Compressed hydrogen storage systems exhibit the lowest degree of system complexity, but also the lowest volumetric storage density. Liquid hydrogen is most dense, but rather suitable for storing larger amounts to achieve a high volume-to-surface-area ratio which determines the boil-off losses. To overcome these losses, permanently a certain amount of hydrogen must be removed. Whereas LOHCs can be stored in normal diesel tanks, they require a complex hydrogen release system. All forms of storage have their pros and cons and every form is suitable for certain applications.

Onboard the vessels, the chemical energy stored in the hydrogen can be converted to electricity and mechanical propulsion energy by means of internal combustion engines or fuel cells and electric motors. Fuel cells neither emit any unburnt hydrocarbons nor nitrogen oxides while creating less vibrations and by trend exhibiting the higher efficiency. Combustion engines offer proven robustness, reliability and durability as well as lower costs. To operate conventional internal combustion engines on hydrogen, several components have to be modified. This can be done for new engines and as retrofit.

To represent the heterogeneous fleet of IWT vessels, four exemplary types of ships have been defined. A cargo vessel, a pushed convoy, a cabin vessel and a Rhine ferry. For each of these ships the necessary amount of hydrogen is calculated based on typical operational profiles and compared to the boundary conditions in respect of the constructional integration. The requirements of each type of vessel regarding operation are defined and contrasted with the technical features of the energy storage and conversion technologies. This analysis reveals four promising technical solutions for each type of vessel. These can be compressed hydrogen storage for the cargo vessel and the ferry and liquid hydrogen storage for the pushed convoy and the cabin vessel. As energy converters, combustion engines are favored for the cargo vessel and the pushed convoy, whereas fuel cells can be promising for the cabin vessel and the ferry. It should be noted that also other combinations are possible and should be evaluated based on concrete machinery space concepts and the specific operational profile.

This study is complemented by an analysis of the legal situation and a proposal of possible education and training concepts.

8 Action Guidance

As laid out in the preceding chapters of this study, hydrogen generated from renewable energy sources constitutes a promising choice as alternative fuel in inland navigation on a mid and long term perspective. Because of the small size of the inland navigation sector in comparison to the sectors of other modes of transport and its small and mid-sized corporate structure a sustainable implementation of hydrogen technologies in inland navigation will rely on public funding for market activation and needs to be embedded in a cross-sectoral strategy.

The European Union as well as several member countries have acknowledged the potentials of hydrogen as energy source and have launched different hydrogen roadmaps and implementation strategies. The European Commission has supported development of hydrogen and fuel cells since the early 1990s. Research has mainly been directed towards performance and durability improvement and cost reduction. Hydrogen and fuel cell technologies were identified amongst the new energy technologies needed to achieve a 60 % to 80 % reduction in greenhouse gases by 2050, as presented in the European Strategic Energy Technology Plan along with the Energy Policy Package in January 2008.

The potential for fuel cells and hydrogen to enhance energy security and mitigate climate change was recognized in 2003 with the creation of the Hydrogen and Fuel Cell Technology Platform. The platform brought together key stakeholders in the fuel cell and hydrogen fields who jointly developed an implementation plan. Published in 2007, the plan addressed the technological and non-technological barriers to deployment of these disruptive technologies. It identified key issues and priorities for accelerating deployment of portable, stationary and transport applications. The platform led to the formation of a Public Private Partnership - the 'Fuel Cells and Hydrogen Joint Undertaking' (FCH JU) - between the European Commission, industry and the research community. A main goal of the FCH JU is to enable commercial deployment by 2020. The European Commission channels support for fuel cell and hydrogen research and demonstration through the FCH JU. For the period 2007-2013, European Commission support amounted to 470 million €. For the period from 2018 it was stated by the Commission that the FCH JU will remain the core of its hydrogen strategy but that it will be complimented by funds from CEF or TEN-T. Demonstrators will be funded via the EU Emission Trading System (ETS) Innovation Fund or the European Investment Bank (EIB).

Together with the Scandinavian Countries, France and the UK, Germany is one of the four major European players in the development of hydrogen in the transport- and energy sector. Based on the German government’s 2016 to 2026 hydrogen and fuel cell technology program, the interdisciplinary National Innovation Program Hydrogen and Fuel Cell Technology ensures the continuation of research and development in the area while simultaneously addressing the pressing issue of market activation and providing necessary support for initial products. The implementation of NIP is conducted via the corresponding measures of the federal ministries involved. The Federal Ministry of Transport and Digital Infrastructure (BMVI – Bundesministerium für Verkehr und digitale Infrastruktur) is initially allocating a sum of 250 million euros until 2019 to support hydrogen and fuel cell technology. The Funding Guideline for “Measures of Research, Development and Innovation” / (Förderrichtlinie für “Maßnahmen der Forschung, Entwicklung und Innovation”) was already published on 29 September 2016 [BMV16].

With the Funding Guideline for “Market Activation Measures within the Framework of the National Innovation Programme Hydrogen and Fuel Cell Technology Phase 2 (Focus: Sustainable Mobility)” / (“Maßnahmen der Marktaktivierung im Rahmen des Nationalen Innovationsprogramms Wasserstoff- und Brennstoffzellentechnologie Phase 2 (Schwerpunkt Nachhaltige Mobilität)” of 17 February 2017, the BMVI supports the market activation of products that have attained market maturity but are not yet competitive in the market, as a preliminary step of the market launch.

The Federal Ministry for Economic Affairs and Energy (BMWi – Bundesministerium für Wirtschaft und Energie) will continue supporting applied research and development in hydrogen and fuel cell technology with around 25 million euros annually within the framework of the 6th Energy Research Program. Moreover, in August 2016 the BMWi launched a funding program within the scope of the National Action Plan Energy Efficiency (NAPE – Nationaler Aktionsplan Energieeffizienz) for the procurement of fuel cell heating devices for private customers. The Federal Ministries for the Environment as well as Education and Research continue to be actively involved via the structures of NOW GmbH in the strategic development of NIP.

In the Netherlands, the EU country with the largest inland fleet, the shipping sector (both inland and ocean shipping) have set themselves the objective of achieving a 50% reduction in CO_2 by 2050 in comparison with 2020 levels. The emission reduction objective is part of the “Energy Efficiency and CO_2 Reduction Agreement for Shipping” signed by the Dutch Minister for Infrastructure and Environment. The Dutch “Sustainable Fuels Vision” also identifies hydrogen generated from renewable energy sources as a long term solution for the reduction of transport emissions.

The Netherlands currently has over 100 hydrogen initiatives in various stages of development, and this number is growing. In the specification of the transition pathways of the Dutch Energy Agenda, hydrogen is emerging as one of the pillars of the energy transition, in addition to all kinds of other sustainable and climate-neutral options. To gain greater insight into the role hydrogen may play for the energy transition and the steps that will have to be taken towards achieving this, the Ministry of Economic Affairs and Climate Policy has asked TKI New Gas (Top Sector Energy) to manage the drafting of a Hydrogen Roadmap which was released in May 2018.

Other countries along the Rhine corridor such as Belgium and Switzerland have their own hydrogen initiatives and are collaborating within EU hydrogen projects. The European and national activities described above form a solid basis and a comprehensive approach for the implementation of hydrogen in the energy and transport sector. Yet, the inland navigation sector as all branches has its particularities and any action taken to promote hydrogen in this field should address these as laid out in the following action guidance.

Infrastructure

Access to a reliable bunkering infrastructure is paramount for the success of hydrogen in inland navigation. Around 85% of all ship transports in Europe are related to or routed on the Rhine Corridor. As pointed out in section 4.1.2, major hydrogen production sites are situated along the industrial centers of the Rhine corridor. Therefore, hydrogen initiatives should focus on sector coupling by further developing this synergy between existing industry and transport infrastructure in the Rhine corridor to establish the necessary bunkering infrastructure.

Optimized funding schemes for inland waterway transport (IWT) pilots and promoting collaboration

This study examines hydrogen solutions for four exemplary vessels with different boundary conditions regarding their specific tasks and field of operation. Even though this examination is only a rough overview, it can be concluded that the optimal layout of the conversion technology and the type of storage can vary between the different types of ships and even within these groups between their field of operation and the given boundary conditions. Therefore, funding should be open to all possible hydrogen technology solutions including both fuel cells and internal combustion engines.

Most hydrogen IWT projects focused on feasibility and concept studies. For further development case studies are needed. However, the conditions of most funding schemes often neglect the business structure of the IWT sector and therefore exclude it from taking part in major hydrogen programs. Small and midsized businesses in inland navigation are often overburdened by the application procedures and the documentation required within European and national projects. Lacking own capital for investments is also a significant barrier for project-involvement of these enterprises.

In order to promote the implementation of hydrogen in the IWT-Sector, various measures and paths should be combined in an integral approach of new funding schemes. In order to overcome economical barriers subsidies for hydrogen propulsion systems are required. For the remaining own contributions access to suitable loans has to be ensured.

However, these components for capital expenditure are not sufficient as long as no savings in operational costs or other ways for the return of investment can be achieved. Therefore, an attractive framework needs to be established e. g. by excluding hydrogen from taxation or reducing port fees for green ships.

The public sector should also promote collaboration between inland shipping companies, research and development facilities, the energy sector, shippers and customers with interest in hydrogen applications. The conversion of public authority ships to hydrogen can serve as a forerunner for commercial inland navigation.

Technical Regulation for Hydrogen Use in IWT

The technical regulations for inland navigation in Europe are developed in a collaborative process between the stakeholders under the umbrella of the European committee for drawing up common standards in the field of inland navigation (Comité Européen pour l'Élaboration de Standards dans le Domaine de Navigation Intérieure – CESNI). CESNI was founded in 2015 by the EU-Commission and the CCNR. The current German presidency of the CCNR has made the development of technical regulations for the use of hydrogen in inland navigation one of their priorities. It can be expected that the development of appropriate regulations will be included in the CESNI working program for 2019-2021. This action should be strongly supported by the member states and the industry.

Forceful Market Uptake

Inland ships are very durable assets with a life span of 40 years and more. The same accounts for engines used in inland ships which have an expected life span of up to 20 years. Therefore it is almost self-explanatory that renewal rates of ship capacities and engines are very low. To avoid a chicken-and-egg dilemma as can be observed from the market uptake of LNG in inland navigation, a forceful market uptake of hydrogen has to include public funding for engine renewal and the installation of the bunkering infrastructure. With the funding guideline "Nachhaltige Modernisierung von Binnenschiffen" (Sustainable Modernization of Inland Ships) the German Ministry of Transport and Digital Infrastructure has established a practical tool which is open to new technologies and can be developed to the needs of the sector with regard to a hydrogen uptake. Only few other countries up to today have specific funding for the inland shipping sector. The Netherlands for example rely on special depreciations while Belgium only has regional funding for the installation of SCR/DPF-Systems or the renewal of Diesel-Engines. Switzerland has no funding scheme for inland navigation due to its small fleet. Hence, funding schemes on the European level should be examined to develop a level playing field for a hydrogen market uptake in inland navigation. Business economic and financing options for greening innovations in IWT were also discussed extensively within the H2020 project PROMINENT (Reference: Ecorys, "D6.3 Business economic and financing options for greening innovations in IWT/D6.5 Financial impact of Greening IWT for Europe”, April 2018, www.prominent-iwt.eu) [PRO18]. The proposed greening fund also includes a so-called sector contribution in terms of a differentiated surcharge on fuel costs which is increased for ships with older emission standards. These topics are currently also discussed within CESNI’s Economic Committee.

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