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CHAPTER 4

Economics of Hydrogen

Martin Robinius, Simonas Cerniauskas, Reinhard Madlener, Christina Kockel, Aaron Praktiknjo, and Detlef Stolten

1 Introduction

Concerns about the growing greenhouse gas emissions and associated anthropogenic climate change call for new solutions for developing a decarbonized and more sustainable energy system. Hydrogen can be a versatile non-fossil energy carrier and has substantial potential to enable such a

M. Robinius (✉)
Institute of Energy and Climate Research, Techno-economic Systems Analysis (IEK-3), Forschungszentrum Jülich GmbH, Jülich, Germany

JARA-ENERGY, Jülich, Germany

umlaut energy GmbH, Aachen, Germany
e-mail: martin.robinius@umlaut.com

S. Cerniauskas
Institute of Energy and Climate Research, Techno-economic Systems Analysis (IEK-3), Forschungszentrum Jülich GmbH, Jülich, Germany

RWTH Aachen University, c/o Institute of Electrochemical Process Engineering (IEK-3), Forschungszentrum Jülich GmbH, Jülich, Germany

R. Madlener
School of Business and Economics / E.ON Energy Research Center, Institute for Future Energy Consumer Needs and Behavior (FCN), RWTH Aachen University, Aachen, Germany

Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

JARA-ENERGY, Aachen, Germany

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transition. This chapter provides an extensive overview of the technical and economic characteristics of hydrogen and outlines the necessary background to foster the discussion of the role of hydrogen in a decarbonized energy system. First, we review potential applications of hydrogen and estimate its market potential in a typical industrialized nation in the year 2050. Subsequently, hydrogen-related policies and regulations are discussed. Then, we describe the most important facets of hydrogen supply, including its production, storage, processing and conditioning, delivery, and refueling. Then, the public acceptance and security aspects of hydrogen fuel supply chains and use are addressed. Finally, we analyze consumer willingness to pay for hydrogen technologies.

2 Hydrogen Use and Markets

Hydrogen can be used in many different sectors, including transportation, households, commerce and trade, chemical and heavy industry, and power sectors (Fig. 4.1). Therefore, hydrogen is increasingly considered a highly promising energy carrier necessary to achieving a fully decarbonized energy system (Robinius et al. 2017a; Henning and Palzer 2013; Knor et al. 2014). To provide a brief overview of hydrogen applications and related market potentials, anticipated hydrogen utilization in different sectors of the energy system will be described. More than 99% of the current worldwide hydrogen demand of 74 million tons arises from the heavy and chemical industry sector (SRI 2007; IEA 2019). Thus, hydrogen already plays today a vital role in this sector.

C. Kockel
School of Business and Economics / E.ON Energy Research Center, Institute for Future Energy Consumer Needs and Behavior (FCN), RWTH Aachen University, Aachen, Germany

A. Praktiknjo
School of Business and Economics / E.ON Energy Research Center, Institute for Future Energy Consumer Needs and Behavior (FCN), RWTH Aachen University, Aachen, Germany

JARA-ENERGY, Aachen, Germany

D. Stolten
Institute of Energy and Climate Research, Techno-economic Systems Analysis (IEK-3), Forschungszentrum Jülich GmbH, Jülich, Germany

JARA-ENERGY, Jülich, Germany

RWTH Aachen University, c/o Institute of Electrochemical Process Engineering (IEK-3), Forschungszentrum Jülich GmbH, Jülich, Germany

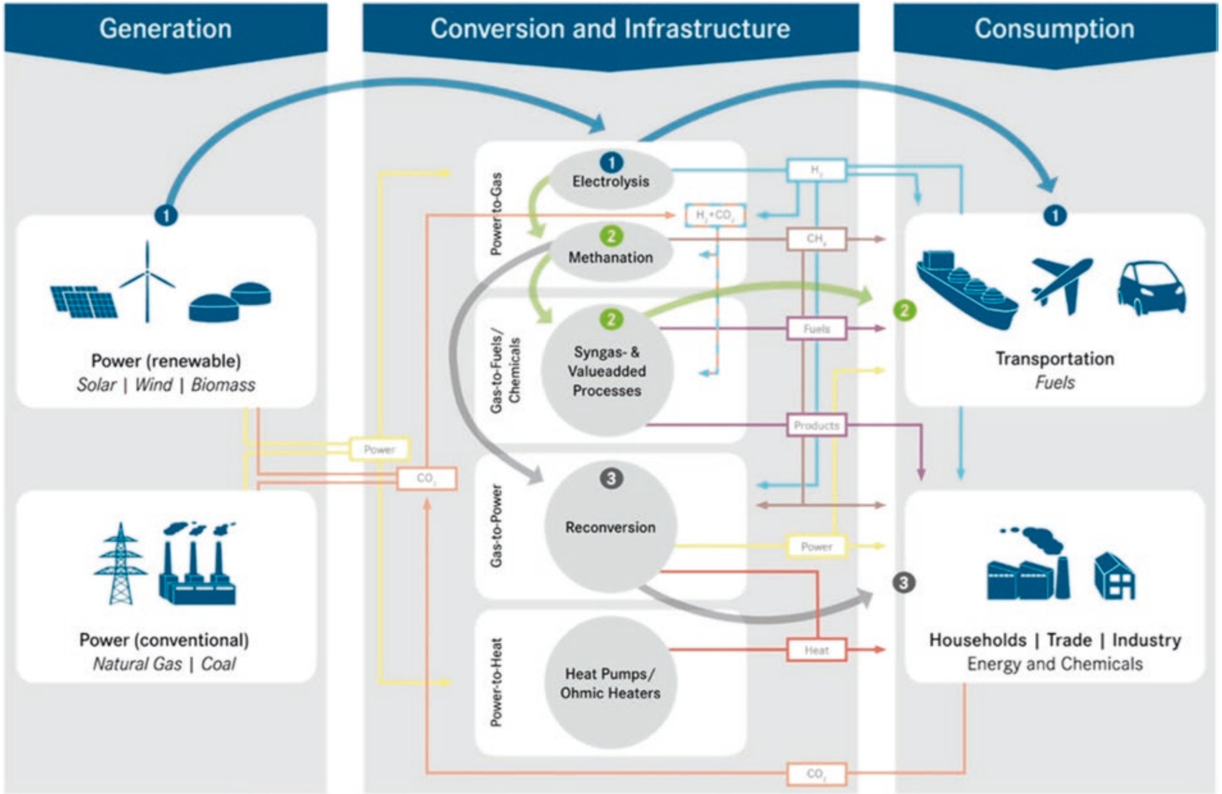


Fig. 4.1 Overview of hydrogen's potential role in the energy system (Robinius et al. 2017b)

2.1 Transport

In the transportation sector, hydrogen can be utilized in conventional combustion engines or, more prominently, to supply fuel cells, which have significantly higher efficiencies than combustion engines and, unlike diesel or gasoline engines, emit no CO_2 and NOx into the atmosphere. Compared to alternative zero emission drivetrains, fuel cell-electric vehicles (FCEVs) offer the advantages of long range (>500 km) and short refueling times (less than 3–5 minutes), as well as comparably high power capacity for heavy duty and commercial applications (Offer et al. 2010). However, the high cost of fuel cells and underdeveloped hydrogen infrastructure has until now limited the market penetration of FCEVs (Gnann et al. 2015). Due to its size and high willingness to pay, the most prominent target market for FCEVs historically was that of passenger cars. To fulfill the high vehicle space and design requirements of passenger vehicles, FCEV cars are generally equipped with 700 bar of onboard hydrogen storage. The first prototypes of FCEVs had already entered development in the 1960s (Fuel Cells Bulletin 2016). The technology has been continuously developed, and today, under the support of various market introduction policies, there are approximately 11,000 FCEV passenger cars on the road worldwide (Fukui 2019).

Despite the slow progress of FCEVs in the passenger car segment, the technology is attracting growing interest in various other applications, such as public transportation and commercial vehicles (Wulf et al. 2018a). Due to their space and design constraints, these vehicles are generally operated with onboard hydrogen storage at 350 bar. Range constraints, limiting the functionality of battery-electric vehicles (BEVs) for commercial vehicles, create a market opportunity for the introduction of fuel cells in local buses, smaller passenger trains and freight vehicles (Ritter 2016; Alstom 2018; Roland Berger 2015; FCH JU 2016). Another application that has been exhibiting significant growth in recent years is the material handling vehicle (MHV) market (Micheli and Hanke 2015). Fast refueling, emission-free operation, and a wide range of possible operating temperatures (i.e., harsh weather conditions) enable fuel cell MHVs to save costly space in logistics centers and operate indoors also at low temperatures as, for example, typically found in cold storages (Fischedick 2017). Other potential FCEV applications expected to play a role in the future energy system include motorbikes, ships, airplanes, railways, and agricultural machinery (Hart et al. 2015; New Holland Agriculture 2014; Hof et al. 2017).

It was found that the associated market potential of captive fleets, such as public transport and forklifts, is sufficient to provide a cost-competitive, countrywide hydrogen supply (Cerniauskas et al. 2019a). From infrastructure perspective, larger mobility markets, such as those for freight vehicles and passenger cars, require a public hydrogen refueling station network, and therefore, these markets are more challenging to enter. Finally, green hydrogen could play a key role in the future production of synthetic fuels, such as synthetic gasoline, synthetic kerosene, and so on, which are among the main options for decarbonizing air travel and high-power vehicles such as locomotives.

2.2 *Private Households and Heat*

Hydrogen can be flexibly used in the heating sector to achieve various inlet temperature levels, thus giving it a broad range of applications (e.g., space heating, hot water preparation), from single-family houses to large, multistorey commercial and residential buildings. Existing natural gas boilers can be retrofitted to use hydrogen, as it has a similar Wobbe index as natural gas (Hodges et al. 2015). Given sufficient hydrogen supply infrastructure, this approach would allow rapid decarbonization of the heating sector, as a successful large-scale retrofit of heating appliances has already been demonstrated during the shift from town gas to natural gas in the first half of the twentieth century and during the still ongoing shift from low- to high-calorific natural gas (Dorrington et al. 2016; Fernleitungsnetzbetreiber 2017). Nevertheless, the blending of hydrogen with natural gas is currently limited by natural gas quality requirements, which vary significantly among countries, from 0.01 to 12%vol. (ITM Power PLC 2013; Dolci et al. 2019). The thermal use of admixed hydrogen and the cost-competitiveness of natural gas make this market more difficult to penetrate than is the case of mobility applications.

In fact, due to its low exergetic efficiency, the combustion of hydrogen is the less preferred utilization option. Alternatively, hydrogen can be used to operate combined heat and power units (CHPs), which are increasing in importance in decentralized energy systems (Weidner et al. 2019). Fuel cell CHPs enable an even higher overall efficiency (equivalent to a coefficient of performance (COP) of >5) than an all-electric solution, which combines the highest efficiency combined-cycle gas turbine (efficiency of >50%) with the highest efficiency heat pump (COP 3–4) (Staffell 2015). In Rigas and Amyote (2013), the effectiveness of support schemes for micro fuel cells in Germany is analyzed against the latest market conditions, support schemes, and legislative changes. The study shows that the technology is still far removed from competitiveness in domestic applications in Germany and that PEMFC system costs must be halved for the representative system considered (viz. from €19,500 to €10,500), including all auxiliary devices, before the technology can compete on the market without any form of subsidy.

2.3 *Chemical and Heavy Industry*

Hydrogen already plays a vital role in the heavy and chemical industry sector. However, instead of being used as an energy carrier, hydrogen is mostly utilized as a chemical feedstock for ammonia and methanol production and in the refining of oil (SRI 2007). Smaller hydrogen demand can also be found in the food-processing sector and in glass manufacturing (Schenuit et al. 2016).

Furthermore, hydrogen can be used for the direct reduction of iron ore and thus foster the decarbonization of the still very GHG-intensive steel industry (Otto et al. 2017).

However, the penetration of green hydrogen in the chemical and heavy industry sector, which encompasses the use in current chemical processes as well as novel applications such as the direct reduction of iron (Power-to-Steel) and the production of synthetic fuels (Power-to-Fuel), is more difficult than in transport. The high cost-competitiveness of the global commodity markets, as well as technological and market development uncertainties, significantly diminish the willingness of industrial consumers to shift to green hydrogen in the short- to medium-term perspective. Therefore, the large-scale adoption of green hydrogen in the industry is generally anticipated during the later stages of the hydrogen market development (Fraunhofer ISI and Öko-Institute 2015; Hydrogen Council 2017). Finally, green hydrogen could play a key role in the future production of synthetic fuels, such as synthetic gasoline, synthetic kerosene, and so on, which are among the main options for decarbonizing air travel and high-power vehicles such as long-haul trucks.

2.4 Power Sector

The growing capacity of variable renewable energy sources, such as wind and solar PV, increases the need for storage systems to buffer energy production fluctuations and provide sufficient flexibility to meet current supply security requirements. Short-period hourly and daily fluctuations can be absorbed by conventional pumped hydro power and more novel solutions, such as state-of-the-art compressed air and battery storage technology. However, the seasonal variation of renewable energy technologies requires long-term storage spanning weeks to months, which can be provided by underground chemical storage by means of hydrogen or synthetic methane (Welder et al. 2018). The stored energy can be shifted to transportation, heat, and heavy industry sectors or converted back into electricity with dedicated open-cycle gas turbines. However, the higher electrochemical conversion efficiency of fuel cells (60%) than of gas turbines (40%) favors coupling with other sectors over repowering. On this, various studies have suggested that hydrogen electrification would play a pivotal role in the power sector with a high degree of renewable power penetration (Henning and Palzer 2013, 2015; Knor et al. 2014). The economic feasibility of power-to-gas (P2G) systems in combination with hydrogen (and renewable methane), as well as underground storage used for load-balancing, is analyzed in Roche et al. (2010) employing a techno-economic model. The authors found that in none of the cases investigated (i.e., base case; storage and arbitrage; storage and balancing) was the P2G system economically viable under present market conditions, and so it requires substantial financial policy support.

3 Potential Applications of Hydrogen

3.1 Hydrogen Policy and Regulation

The literature on hydrogen policy and regulation has been growing in recent years, especially regarding green (Fig. 4.2) hydrogen in transport (Ajanovic and Haas 2018; Bleischwitz and Bader 2010; Collantes 2008; Rodrígueza et al. 2019; Pique et al. 2017). The economic prospects and necessary policy framework for green hydrogen used in passenger car transport are investigated by Ajanovic and Haas (2018), taking into account hydrogen production costs from variable renewable energy technologies and learning curve effects concerning fuel cell vehicles. The authors conclude that the prospects for hydrogen, apart from the need to become economically viable, depend a lot on the prevailing policy framework (to foster low-emission vehicles), for example, in terms of vehicle taxation/subsidization (purchase and use), non-monetary measures (entry to city centers, use of bus lanes, the free use of public parking spaces, etc.), and fuel economy standards. Bleischwitz and Bader (2010) review the current EU policy and regulatory framework for the transition toward a hydrogen economy, with a particular focus on prevailing barriers and inconsistencies. The authors conclude that the present policy framework does not hinder hydrogen development but that it does not forcefully compel it either. The most substantial impact is on hydrogen and fuel cell research and development. Regulatory policies are found to have a weak but positive impact on hydrogen, whereas EU funding policies show some inconsistencies. In their view, the large-scale market diffusion of hydrogen and fuel cells will require a new, technology-specific support approach, with a supportive policy framework that takes the regional dimension explicitly into account. However, recent changes in the EU Renewable Energy Directive, which includes green hydrogen

Brown	Coal gasification
Grey	Water electrolysis using power from fossil fuels
	Reforming of natural gas
White	By-product of industrial processes
Blue	Coal gasification with CCS
	Reforming of natural gas with CCS
Turquoise	Methane pyrolysis
Yellow	Water electrolysis using nuclear power
Green	Reforming of biogas
	Gasification and fermentation of biomass
	Water electrolysis using regenerative power sources

Fig. 4.2 Color coding for origins of hydrogen

as a feedstock switch in refineries, indicates the increasing consistency of EU policy (European Parliament and Council 2018).

The manifold dimensions of the policy debate over transportation fuels, with a particular focus on hydrogen, are analyzed in Collantes et al. (Collantes 2008) for the US, based on a web-based survey involving 502 individuals from 323 different stakeholder organizations. Policy beliefs and policy preferences of stakeholders are collected in order to identify, and obtain measures of, the main dimensions of the policy debate related to the use of hydrogen as a transportation fuel in the US, thus greatly reducing the complexity of the policy picture. Three policy preferences found are (i) command-and-control approaches; (ii) addressing externalities with technology-neutral approaches; and (iii) facilitating technological progress and innovation. Another effort to translate the potential contributions of hydrogen technology into public policy schemes was undertaken in Rodrigueza et al. (Rodrígueza et al. 2019) in the case of the legal framework for hydrogen regulation in Mexico. The study found that the lack of hydrogen storage, lack of regulation on the use of hydrogen in final applications, and lack of safety regulation are essential barriers that must be overcome before the hydrogen economy can unfold. Finally, Pique et al. (2017) report on a comparative study on regulations, codes, standards, and practices on hydrogen fueling stations in nine different countries, namely, the US (California), the UK, Italy, Germany, Canada, Sweden, Norway, Denmark, and Spain. The authors find that countries often have no national regulation specific to hydrogen fueling, have no specific regulations other than their own technical guidelines, and that international standards (such as ISO 17268 or ISO 20100) are the references applied in almost all countries.

Leibowicz (2018) develops policy recommendations for the transition to sustainable mobility and transport system by investigating the historical dynamics of this sector, and in particular, regularities concerning the relative timing of infrastructure, vehicle, and travel diffusion processes across systems. In doing so, he analyzes technological lock-ins, techno-institutional complexes, technology transitions, barriers to adoption, and the historical diffusion of transport systems.

4 Hydrogen Infrastructure

4.1 Production

Hydrogen can be separated from water or hydrocarbon compounds found in various fossil fuels and biomass. The element hydrogen is colorless, but due to the broad spectrum of possible production alternatives, there exist different names to classify the hydrogen according to its CO_2 emissions, like gray, blue, and green hydrogen (IEA 2019) (see Fig. 4.2). In general, the term gray hydrogen refers to hydrogen production via fossil fuels, with the most common process being the steam methane reforming (SMR). Depending on the CO_2 intensity of the electricity mix, production via electrolysis from the grid electricity may also be called gray hydrogen due to the high associated CO_2 emissions. Nonetheless, additional sub-classes to the CO_2 intensive production, such as brown and white hydrogen, have been proposed. Brown hydrogen stands for hydrogen production from coal and is the most CO_2 intensive among the production sources. By-product hydrogen that is not used as feedstock but is exploited thermally near its source was proposed to be referred to as white hydrogen. In the case of other use cases, the thermal utilization on-site can be substituted by the combustion of natural gas, thus leading to a smaller CO_2 intensity than in the case of the gray hydrogen. Blue hydrogen generally refers to non-renewable hydrogen production meeting low CO_2 intensity criteria. Application of carbon capture and storage (CCS) to coal gasification and SMR enables these processes to sufficiently reduce the associated emissions to meet this criterion. However, additional classes of the turquoise and yellow hydrogen have been proposed. Turquoise hydrogen is produced by methane pyrolysis, in which methane is split in a thermochemical process into solid carbon and hydrogen, and if the heat supply of the high-temperature reactor is provided by renewable energy sources, the process yields low CO_2 emission intensity, whereas hydrogen production via electrolysis from nuclear power is called yellow hydrogen. Green hydrogen is produced exclusively from renewable energy sources. Typically, green hydrogen is produced by water electrolysis. Further possibilities are the gasification and fermentation of biomass and the reformation of biogas. The following sections will explore the key features of the essential hydrogen production processes defining the described classification.

Currently, the most widely utilized options to retrieve hydrogen from hydrocarbons are SMR, partial oxidation, and gasification (gray hydrogen) (SRI 2007). SMR comprises a high-yield endothermic reaction of natural gas and steam to allow high-purity hydrogen production (Gupta 2008). The partial oxidation of hydrocarbons has lower material efficiency and hydrogen purity but can utilize a larger variety of fuels, including oil residues (Gupta 2008). Gasification has the lowest material efficiency and hydrogen purity; however, it allows the use of more widely accessible fuels, such as coal (brown hydrogen) and biomass (Gupta 2008) [43]. Against the background of CO_2 emissions reduction policies, these processes can be extended with subsequent CCS (blue hydrogen), thus enabling to diminish the CO_2 footprint of hydrogen production, which is expected to be the key bridge technology to the widespread low-emission hydrogen production (IEA 2019). Another possibility of providing hydrogen while avoiding CO_2 emissions is methane pyrolysis (turquoise hydrogen), which uses the thermal non-catalytic splitting of methane into hydrogen and carbon at high temperatures. However, despite up-and-coming applications, due to its low technology readiness level (TRL), methane pyrolysis is not expected to become commercially available within the next 10–20 years (Geres et al. 2019). To put the state of technology's development into perspective, the latest pilot project aims to reach a production capacity of up to 12 kg_{H2}/h (ARENA 2019) which is approximately equivalent to production of an electrolyzer with 600 kW_{el} capacity with running on full load

SMR

Property	Low	High
$\eta_{LHV,CH4}$ %	70	78
Cost €/kg_{H2}	1.0	2.2

TRL: 9

Advantages:
Low cost H_2 production
Established technology
Scalable process

Disadvantages:
High CO_2 emissions

Selected projects:
Corpus Christi (USA)
Ludwigshafen (GER)

SMR+CCS

Property	Low	High
$\eta_{LHV,CH4}$ %	70	78
Cost €/kg_{H2}	1.2	2.8

TRL: 8

Advantages:
Intermediate CO_2 emissions
Medium cost H_2 production
Scalable process

Disadvantages:
Intermediate CO_2 emissions
Requires CO_2 infrastructure

Selected projects:
H21 (GBR)
H2 Magnum (NLD)

Methane Pyrolysis

Property	Low	High
$\eta_{LHV,CH4}$ %	55	75
Cost €/kg_{H2}	1.0	2.5

TRL: 5

Advantages:
No CO_2 emissions
Black carbon as byproduct
Low cost H_2 production

Disadvantages:
Tradeoff of H_2 and carbon quality
No clearly preferred process

Selected projects:
Hazer (AUS)
Monolith (USA)

SMR: Steam Methane Reformer **CCS:** Carbon Capture and Storage **LHV**: Lower Heating Value
TRL: Technology Readiness Level

Fig. 4.3 Comparison of natural gas-based hydrogen production methods (Geres et al. 2019; ARENA 2019; Monolith Materials 2018; Parkinson et al. 2019; Sarsfield-Hall and Unger 2019; Eikaas 2019; Machhammer et al. 2016; Abánades et al. 2013)

at all hours in a year. Figure 4.3 provides an overview of the most promising low CO_2 intensity production options from natural gas.

Alternatively, with expanding decarbonization of electricity production (green and yellow hydrogen), by using electrolysis hydrogen can be retrieved from water. The main electrolysis processes currently being discussed are alkaline (AEL), polymer electrolyte membrane (PEMEL), and solid oxide (SOEL) electrolysis. AEL is the most mature technology and is already implemented on an industrial scale of several MW and is used for 4% of current hydrogen production (SRI 2007). Due to its typical application for chlorine production instead of variable renewable energy integration, AEL has important constraints on the operating range, requiring a minimal load of 20% and relatively slow dynamics between operating points of <30 s (Schmidt et al. 2017a; Brinner et al. 2018). Alternatively, PEMEL has a wider operating range of 0%–150% and dynamic operation between operating points of <2 s, thus enabling the coupling of PEMEL with highly intermittent power sources such as solar PV and wind (ITM Power 2018; Bayer et al. 2016; Kopp et al. 2017) [55–57]. Another alternative is SOEL, which operates at high temperatures (700–1000 °C with ZrO_2 ceramic as electrolyte) that allow higher efficiency than in the case of other electrolyzer systems (Brinner et al. 2018). However, the high operating temperature also increases the thermal inertia and thus feasible size of the cells, which poses significant challenge for larger scale SOEL deployment and integration with variable renewable energy technologies. Furthermore, current SOEL must overcome important deficiencies, such as

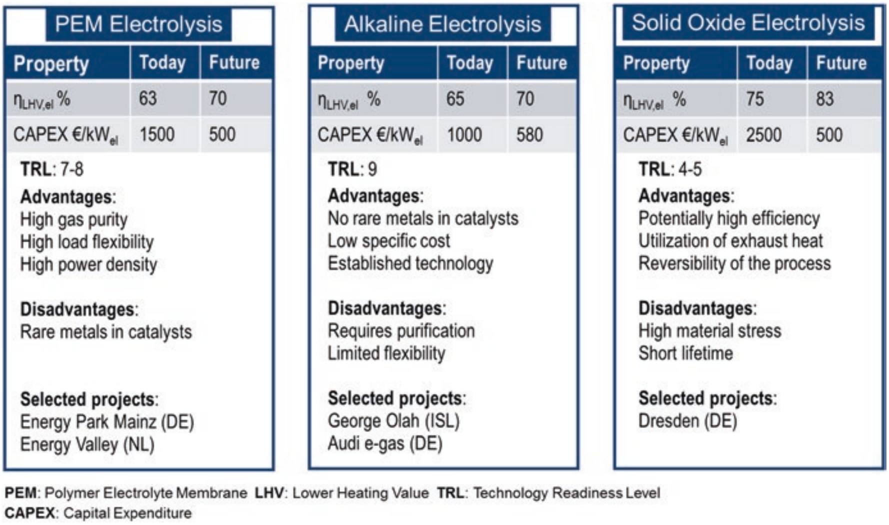


Fig. 4.4 Comparison of electrolytic hydrogen production methods (Wulf et al. 2018a; Brinner et al. 2018; Schmidt et al. 2017b; Saba et al. 2018; Glenk and Reichelstein 2019; Smolinka et al. 2018)

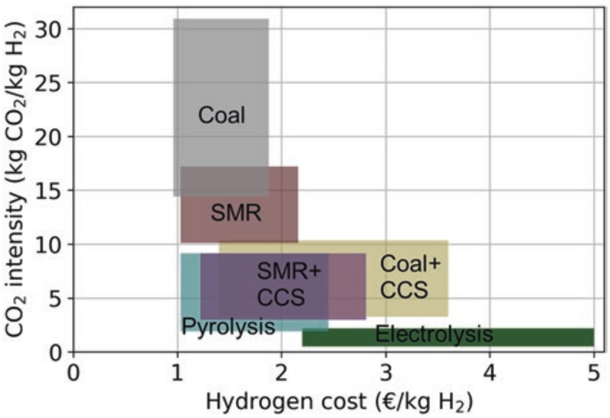


Fig. 4.5 Hydrogen production cost and intensity (adapted from the literature (Parkinson et al. 2019; Heuser et al. 2019))

short lifetimes and material degradation (Schmidt et al. 2017a). Figure 4.4 provides an overview of the most important features of electrolytic hydrogen production technologies.

Figure 4.5 summarizes the literature review of the CO_2 intensity and the cost of hydrogen production for a selection of the most promising technologies. The results consider estimates of life-cycle emissions of the production and primary energy sources. In the case of coal-based processes, underground mined coal, and in the case of electrolysis, renewable electricity is considered in the analysis. Furthermore, emissions occurring in the natural gas supply chain are additionally considered for SMR and SMR+CCS (Munnings and Krupnick 2018). The respective technologies are displayed as areas encompassing underlying uncertainties and variations of the data in the literature. The displayed variation of fossil fuel-based production is mainly affected by efficiency and the costs of primary energy and CCS where applicable, whereas in the case of electrolysis, the uncertainty appears primarily due to different renewable energy availability and anticipated future technological development of electrolysis and renewable energy generation technologies. It can be observed that moving from top to bottom along the y-axis, these technologies display a Pareto frontier of both hydrogen production cost and associated CO_2 intensity. Whereas, on the one hand, coal and SMR lead to not only lowest cost but also highest CO_2 emissions, on the other hand, green electrolytic hydrogen enables the lowest CO_2 emissions at the cost of higher production costs. In between, one can observe pyrolysis and coal as well as natural gas-based hydrogen production with CCS. Nevertheless, as mentioned above, pyrolysis is still at an early stage of development. Thus, the initial transition to less CO_2 intensive production will potentially not be able to rely on this technology.

4.2 Storage

Seasonal variations of renewable energy sources such as wind and solar PV require long-term storage solutions to cope with intermittent power production. The long-term storage requirements of renewable energy integration can be fulfilled with hydrogen. Hydrogen storage can be facilitated by the storage of pure hydrogen or by using hydrogen carriers (Reuß et al. 2017). Pure hydrogen can be stored in specialized steel containers in a compressed, liquid state or, alternatively, compressed hydrogen can be stored in underground facilities. The high storage capacity and relatively low costs of underground storage make it an especially attractive solution for seasonal renewable energy variations. Gaseous and liquid storage options, by contrast, are more suitable as buffer systems at hydrogen refueling stations. Since the 1960s, the utilization of underground storage in industrial facilities has proven the technical feasibility of GWh-scale underground hydrogen storage (Crotogino et al. 2010). However, despite large potential in Europe and some other regions, the geological limitations of the required rock formations for salt caverns and porous rock diminish the global availability of hydrogen underground storage (and multiple media may compete for underground storage, such as compressed air, CO_2, and hydrogen itself). Alternatively, hydrogen can be stored in the form of synthetic fuels or by making use of specialized energy carriers. While the use of synthetic fuels would allow the existing infrastructure to be used, drawbacks include high energy losses during the conversion and the cost of CO_2 separation from the air, as it is anticipated to decarbonize the energy

Salt Cavern[1]

Property	Today	Future
Density GJ/m³	1,44	1,44
CAPEX €/kg_{H2}	21	21

TRL: 8-9
Advantages:
Long term storage
Low space demand
Low specific cost

Disadvantages:
Geological constraints

Selected projects:
Clemens Dome (US)
Tesside (UK)

Gaseous H_2 Bundle

Property	Today[2]	Future[3]
Density GJ/m³	2,88	3,84
CAPEX €/kg_{H2}	800	600

TRL[2]: 8-9
Advantages:
Long cyclic lifetime
Established technology[2]
No geological constraints

Disadvantages:
High specific cost

Selected projects:
London (UK)
Oslo (NOR)

Liquid H_2 Tank

Property	Today	Future
Density GJ/m³	8,5	8,5
CAPEX €/kg_{H2}	25	25

TRL: 9
Advantages:
Long cyclic lifetime
Established technology
No geological constraints

Disadvantages:
Requires liquefaction

Selected projects:
Vancouver (CAN)
London (UK)

TRL: Technology Readiness Level
CAPEX: Capital Expenditure
1: Cavern V = 500.000 m³, P = 150 bar
2: Bundle pressure = 350 bar
3: Bundle pressure = 500 bar

Fig. 4.6 Features of hydrogen storage (Wulf et al. 2018a; FCH JU 2016; Brinner et al. 2018; Reuß et al. 2017; Hua et al. 2014; Acht 2013; Yang and Odgen 2007)

system by 2050. Specialized energy carriers, such as hydrides and liquid organic energy carriers, can offer advantageous energy density properties under low pressure, thus mitigating potential hydrogen risks (Reuß et al. 2017). However, these technologies also feature drawbacks in terms of efficient energy discharge and must still be proven in day-to-day operation to demonstrate the technology's readiness for commercialization (Fig. 4.6).

4.3 Hydrogen Processing and Conditioning

The varying technical characteristics of the components along the hydrogen supply chain with respect to the hydrogen's state, purity, and pressure necessitates conversion steps, such as compression, liquefaction, and purification. In the case that energy carriers are used for the storage and transport of hydrogen, charging and discharging units must be taken into consideration.

Electrolytic hydrogen production output is typically conducted between 1 and 20 bar, while to accommodate sufficient quantities of hydrogen and to save space, mobile hydrogen fuel cell applications operate at 350–700 bar. This creates a significant pressure increase that must be maintained and operated along the supply chain. Furthermore, hydrogen supply chain components, such as high-pressure pipelines and 500-bar trailers, have additional hydrogen pressure constraints. To fulfill the aforementioned hydrogen pressure requirements, the compression can be facilitated via mechanical, electrochemical, hybrid, and ionic means. However, only the former is an established technology with proven operational viability. Alternatively, for the gradual pressure increase along the supply chain, hydrogen can be liquefied at the production point and subsequently evaporated and compressed to the required pressure level at the refueling station.

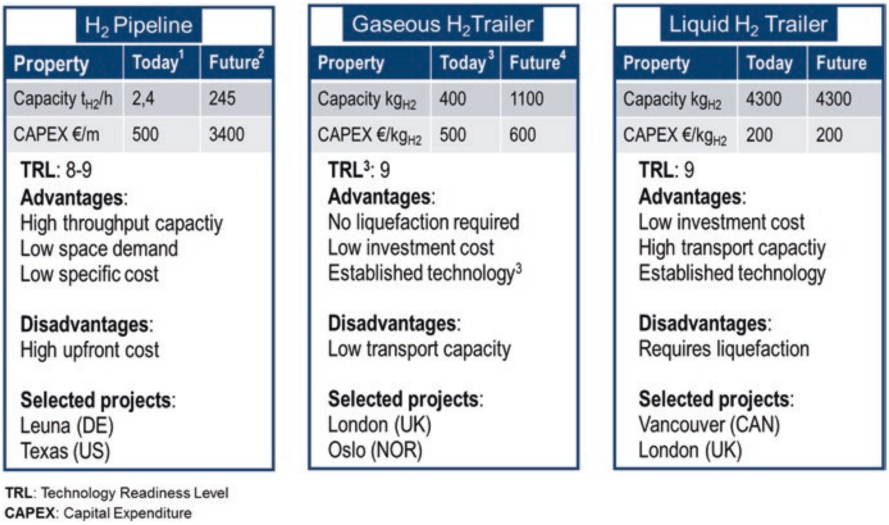
As with the pressure, hydrogen purity is defined by the hydrogen quality requirements of the final consumer; for example, PEMFCs have a 99.97% purity requirement (ISO 2012). However, depending on the hydrogen supply chain pathway used, additional hydrogen purity constraints can arise when SMR and by-product hydrogen or hydrogen liquefaction are considered (Berstad 2018; Zhu et al. 2018). The most widely adopted hydrogen purification methods encompass temperature swing adsorption (TSA) and pressure swing adsorption (PSA). Special membranes also are promising for smaller throughput applications.

4.4 Hydrogen Delivery

The three main routes of hydrogen distribution are gaseous hydrogen trailers and pipelines, as well as liquid hydrogen trailers. The choice of the most effective delivery method depends on the chosen means of storage, as changes in the state of hydrogen increase energy losses, delivery distance, and throughput (Reuß et al. 2017; Yang and Odgen 2007).

Gaseous hydrogen trailers offer a cost-effective solution during the introduction phase, marked by low and sparsely distributed demand. They become less economical in the later market stages when hydrogen demand increases. Nevertheless, even with significant hydrogen demand, the last mile distribution from the hydrogen pipeline to the refueling station remains a cost-effective option (Reuß et al. 2019). Alternatively, hydrogen can be liquefied or transported in the form of liquid organic hydrogen carriers. Both options enable cost-efficient, long-distance hydrogen transportation, which is especially interesting for overseas hydrogen trade (Heuser et al. 2019). Challenges related to the transport of liquified hydrogen are comparable to those of LNG, which requires high insulation to avoid boil-off losses. Therefore, as with LNG transport, LH_2-transporting ships and trucks can be operated on the boil-off losses of hydrogen. In the case of liquid organic hydrogen carriers (LOHCs), transportation is very similar to liquid fuels, and therefore, few modifications to current fossil fuel pipelines and trailers would be necessary. However, studies have shown that economic viability of LOHCs delivery depend strongly on the availability of low-cost heat energy (Reuss 2019), constraining LOHCs to more specific environments (Fig. 4.7).

Hydrogen pipelines are often considered as the most cost-efficient and environmentally favorable means of delivering large volumes of hydrogen over medium to large distances (Wulf et al. 2018a; Tlili et al. 2020; Emonts et al. 2019). This makes it especially attractive for a transmission network and the connection of industrial sites. Currently, there are already several insulated hydrogen pipeline networks supplying industrial sites with a total length of 3000 km in Europe and the US. The risk of low pipeline utilization and



H_2 Pipeline

Property	Today[1]	Future[2]
Capacity t_{H2}/h	2,4	245
CAPEX €/m	500	3400

TRL: 8-9
Advantages:
High throughput capactiy
Low space demand
Low specific cost

Disadvantages:
High upfront cost

Selected projects:
Leuna (DE)
Texas (US)

Gaseous H_2 Trailer

Property	Today[3]	Future[4]
Capacity kg_{H2}	400	1100
CAPEX €/kg_{H2}	500	600

TRL[3]: 9
Advantages:
No liquefaction required
Low investment cost
Established technology[3]

Disadvantages:
Low transport capacity

Selected projects:
London (UK)
Oslo (NOR)

Liquid H_2 Trailer

Property	Today	Future
Capacity kg_{H2}	4300	4300
CAPEX €/kg_{H2}	200	200

TRL: 9
Advantages:
Low investment cost
High transport capactiy
Established technology

Disadvantages:
Requires liquefaction

Selected projects:
Vancouver (CAN)
London (UK)

TRL: Technology Readiness Level
CAPEX: Capital Expenditure

Fig. 4.7 Features of hydrogen delivery methods (Wulf et al. 2018a; FCH JU 2016; Brinner et al. 2018; Reuß et al. 2017; Hua et al. 2014; Tractebel and Hinicio 2017; Krieg 2012)

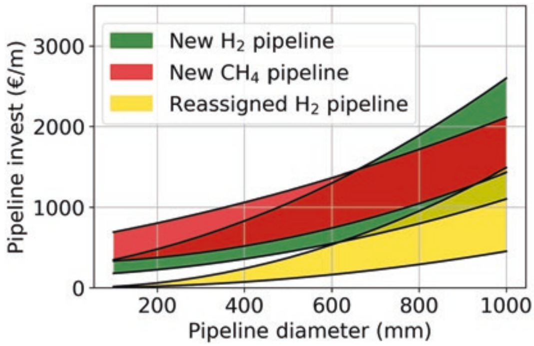


Fig. 4.8 Pipeline investment cost overview (Robinius et al. 2017a; Fernleitungsnetzbetreiber 2017; Krieg 2012; Cerniauskas et al. 2019a; Mischner et al. 2011)

elevated initial investment in the steel pipelines (Fig. 4.8) challenges the implementation of hydrogen pipelines during the market introduction phase. However, pipeline costs can be alleviated through the reassignment of existing natural gas pipelines, which, with the increasing electrification of the heating sector and the shift from low- to high-caloric natural gas, will increasingly become available. Initial investigation of the German natural gas transmission grid has shown that, despite additional measures for handling hydrogen-related material embrittlement, pipeline reassignment can reduce yearly pipeline expenditures by up to 80% in comparison to a new, dedicated hydrogen pipeline (Cerniauskas et al. 2019a). Another option to use hydrogen in the natural gas grid is to blend hydrogen with natural gas. Historically, there have been many cases of utilizing hydrogen-rich town gas (50–60% of H_2), which were abandoned in favor of natural gas in the 1960s (Williams 1981). Currently, different countries make use of hydrogen gas admixtures with natural gas of up to 10% w\m (ITM Power PLC 2013), which can be further increased if heating devices and natural gas turbines and CNG vehicles, which currently allow 2%vol max, are adapted for higher hydrogen concentrations (DVGW 2019). Comparable large-scale change in consumer devices was already observed during the transition from town gas to natural gas in the 1960s, as well as during the ongoing shift from low- to high-caloric natural gas (Fernleitungsnetzbetreiber 2017; Williams 1981). Nevertheless, despite the apparent benefits of the widespread availability of natural gas infrastructure and the avoidance of new infrastructure implementation, hydrogen blending might lock in hydrogen to thermal use, as any other hydrogen applications would require subsequent hydrogen purification (ISO 2012).

4.5 Hydrogen Refueling

Currently, all hydrogen-powered vehicles prefer gaseous over liquid onboard hydrogen storage, as the latter would inevitably lead to boil-off losses in the vehicle. For use in passenger cars, the current state of the art is a gauge pressure of 700 bar, while 350 bar is the prevailing pressure for hydrogen use in buses and other commercial applications. The underlying structure of hydrogen refueling stations is comparable to that of current fossil fuel refueling and consists of a buffer storage, dispenser, cooling unit, and fuel-processing unit that creates the necessary pressure gradient to facilitate refueling. This principle holds for gaseous as well as liquid and LOHC delivery (Pratt et al. 2015). Additional cooling of hydrogen is required to compensate for the temperature increase during refueling, which is caused by the Joule-Thomson effect. Detailed hydrogen refueling station designs generally differ concerning the form of hydrogen delivery and the chosen method for creating the required pressure gradient. For the 700-bar hydrogen refueling of passenger cars, the pressure is increased to 875 bar to enable rapid refueling rates of 1.8–3.6 kg/min (FCH JU 2016; SAE 2014). To achieve this, hydrogen is generally either stored in high-pressure vessels that facilitate the refueling process or medium pressure vessels, with a small additional compressor, which covers the highest pressure-gradient requirements, being installed. In the case of liquid or LOHC hydrogen delivery, hydrogen is evaporated or discharged from the hydrogen carrier and compressed to the required pressure. In the case of 350-bar vehicles, rapid refueling requires a lower pressure gradient, and therefore, 500-bar trailers can be employed as high-pressure hydrogen storage media for vehicle refueling (Elgowainy et al. 2014; Reddi et al. 2017).

5 Hydrogen Safety

In general, concerns about hydrogen safety are different but not more demanding than those pertaining to fossil fuels such as natural gas, gasoline, or diesel (Rigas and Amyote 2013). Most hydrogen hazards relate to the fact that, like methane, hydrogen gas cannot be detected with human senses (Rigas and Amyote 2013). In the case of methane, gas leakage detectability increased with the addition of odorants to the methane gas. However, the current high hydrogen purity requirements of fuel cells preclude the use of odorants (Rigas and Amyote 2013). Nevertheless, hydrogen-related material degradation is a well-understood and -managed hazard, as it is among the main causes of equipment failures in the oil and gas industry (Popov et al. 2018; Shehata et al. 2008). Hydrogen also has positive features when compared to fossil fuels. In contrast to methane and gasoline, hydrogen rapidly disperses to incombustible concentrations and has less explosive energy (Hess Corp 2007; Linde AG 2018; Air Liquide AS 2018). Furthermore, unlike gasoline, hydrogen is neither toxic nor carcinogenic (Hess Corp 2007; Linde AG 2018).

Hydrogen-related incidents are constantly tracked and analyzed to improve the safety of hydrogen system operation. The major causes of hydrogen-related incidents can be classified into the following categories (Federal Institute for Materials Research and Testing 2002):

- Mechanical and material failure
- Corrosion and embrittlement
- Incidents of over-pressurization
- Incidents of expanding liquid hydrogen boil-off
- Hydrogen-unrelated incidents
- Human error

An overview of more than 240 historical incidents revealed that 95% of these were not associated with any fatalities, while 34% did not result in any damage (Rigas and Amyote 2013; Weiner and Fassbender 2011). It could also be identified that most of the accidents occurred as a result of simple equipment, such as valves and fittings, which often relates to human error during assembly and maintenance (H2 Tools 2019). Therefore, despite the fact that most of the accidents were directly caused by equipment failure, the most frequent direct and indirect cause of the accidents was a lack of situational awareness and human error (Rigas and Amyote 2013; H2 Tools 2019).

Markerta et al. (2017) advocate the use of a holistic approach for analyzing the risk and sustainability of hydrogen infrastructures, proposing the use of the "functional modeling" method and combining this with life-cycle analysis (LCA) and geographic information systems (GIS). They consider risk assessment as part of a more general decision plan needed to design and establish sustainable supply chains that are economical, efficient, reliable, safe, and secure. By using functional decomposition (from an early design stage onward), it is possible to analyze and compare alternative supply chain solutions that provide the required system functions with regard to safety, reliability, environmental impact, and costs.

5.1 The Public Acceptance of Hydrogen

The public acceptance of hydrogen technologies has been the subject of research for several decades. Varying levels of acceptance were examined in broad, methodological studies. The following comments highlight only a few selected criteria that relate predominantly to the perception of the general population in Germany (Zimmer 2013a; Spillet and IFOK 2016). An overall positive basic attitude toward hydrogen transportation is often found due to its tailpipe emission-free nature and status as a futuristic technology. One exception was civil society actors surveyed who were reasonably skeptical about hydrogen transportation applications. Citizen surveys focused in particular on expectations of the technology in terms of vehicle usability, health and noise, climate and environmental protection, and safety sensitivity (Zimmer 2013a; Spillet and IFOK 2016). With regard to usability, the interviewees largely assumed current conditions with regard to range, performance, vehicle size, and filling station availability (Zimmer 2013a).

According to the report for Germany, noise abatement played a minor role in the assessment (Zimmer 2013a). The most important added value was considered the technology's contribution to environmental protection. The often critical issue of safety perception due to the chemical-physical properties of hydrogen played hardly any role in the study. The report noted that this was demonstrated by the fact that the hazardous nature of hydrogen was not once addressed. Also, in a citizen conference, after an initial discussion of safety concerns on the part of citizens, the assessment was expressed that hydrogen vehicles are safe. Furthermore, a representative survey was carried out in which approximately 1000 people were asked about their view of the statement, "I would be more afraid to live next to a hydrogen filling station than next to a conventional filling station," with 6% replying that this would be "fully applicable," 17% that it would be "rather applicable," 43% that it would be "rather not applicable," and 34% that it would be "not applicable at all." An overwhelming majority of 77%, therefore, rejected the statement. Zaunbrecher et al. interviewed 182 people about their attitude and acceptance of hydrogen storage in Germany (Zaunbrecher et al. 2016). Of the 141 answers supplied, it could be concluded that hydrogen, in contrast to other currently discussed technologies of the energy system transformation, is generally viewed positively in terms of social acceptance. The construction of necessary facilities is also supported in principle, although there are uncertainties about the risks if hydrogen is stored near residential areas.

Studies on similar questions have also been carried out in other nations. Despite this study's focus on Germany, the results of studies in other countries will be presented briefly, as hydrogen-based passenger car transport can only be successful if it can be implemented worldwide. Iribarren et al. investigated the social acceptance of hydrogen in Spain as a fuel for road traffic (Iribarren et al. 2016). Some central questions included the public perception of hydrogen itself, hydrogen as a fuel in public transport, and its environmental friendliness. All three questions were answered in the affirmative, in some cases at more than 70%. On the question of the acceptance of hydrogen fueling stations, it is striking that more than 50% of those questioned had no objections to these but preferred that they be built away from residential areas. Only about 3% of the respondents were against hydrogen fueling stations. The aspect of supporting the market introduction of hydrogen was examined on the basis of the question of an appropriate ("affordable") tax. A total of 74% responded positively, but around 60% felt that this transition should not be undertaken with the help of a direct tax. Similar findings were found in a trans-European study on hydrogen acceptance as well, thus indicating the underlying societal acceptability and support for hydrogen and fuel cell technology applications (HYACINTH 2013).

A study by Bögela et al. (2018) investigates the implications of prior attitudes for public-facing communication campaigns related to hydrogen technologies in seven European countries, finding low attitude strength and low stability of attitudes with regard to hydrogen fuel cells for both stationary and mobile applications. The implications of these findings are that information campaigns in early stages can help increase awareness among those with no or low prior knowledge about hydrogen technologies and positively influence attitudes toward the technology. At a later stage, when public knowledge and awareness increase, psychological research on prior attitudes becomes more relevant and should address the context-specificity and empirical testing of the theoretical models used.

An interesting question is whether the provision of quantitative risk information on hydrogen infrastructure increases or decreases acceptance (behavior toward the technologies) and acceptability (attitudes). In a repeated Japanese online survey (Ono and Tsunemi 2017; Ono et al. 2019) regarding the scenario of constructing a hydrogen fueling facility at the gas station in the vicinity to the home of the respondents, the public acceptance of hydrogen fueling was investigated on the basis of risk perception scales. The provision of quantitative risk information and risk acceptance criteria increased the acceptability of hydrogen refueling stations in proximity to the homes of respondents but decreased acceptability at the nearest gas station.

Roche et al. (2010) review the various conceptual frameworks and methodologies used for studying public attitudes toward new transport technologies. They review the findings of recent literature on acceptance, attitudes, and preferences for hydrogen and fuel cell end-use technologies from a vehicle perspective. The authors recommend using approaches that build knowledge and familiarity with the technology prior to the exploration of attitudes. They advocate further studies that take a whole-system perspective on hydrogen technologies, looking at (green) hydrogen in the context of other competing CO_2-free fuel technologies, and which aim to identify the early signs of possible social acceptance barriers (to be prepared if opposition arises in the course of increasing the penetration of hydrogen, and in particular concerning growing numbers of hydrogen refueling stations).

5.2 Willingness to Pay

For the broad adoption of hydrogen-based transportation, in addition to the right conditions for supply with FCEVs and hydrogen, the question arises of whether or not consumers are willing to opt for hydrogen-based transport by purchasing an FCEV. According to economic theory, a customer purchases a product or service if (a) the utility it provides exceeds the so-called total cost of ownership (TCO), that is, its net utility is positive, and (b) if its net utility is the highest among all available alternatives (Zweifel et al. 2017). While utility itself is subjective and dependent on the personal preferences of consumers, its influencing factors are measurable. In the case of hydrogen-based transportation, primary drivers certainly take mobility itself (e.g., distances one can travel in a specific timeframe) into account. However, as Hackbarth and Madlener show, there are other factors, such as a reduction of CO_2 emissions, that might add to a consumer's perceived utility of hydrogen-based transportation (Hackbarth and Madlener 2016). With respect to TCO, one can differentiate between fixed and variable costs for consumers. In terms of fixed cost, the most substantial impact is the cost of the vehicle itself. Other fixed costs might include expenditures for taxes or insurance. With variable cost, the most significant factor is the cost of hydrogen as a fuel. Additionally, the maintenance costs depend on the use of FCEVs.

The monetary value of consumers' willingness to pay (WTP) can be quantified using different analytical methods. In general, these approaches can be divided into the actual (revealed) or hypothetical (stated) market behavior of the consumers. On the one hand, the preferences of customers can be revealed through their actual purchasing behavior in the markets. Using observations of actual market transactions, highly reliable and valid data on consumer preferences can be obtained (Schmidt and Bijmolt 2019). From volumes purchased as a function of market prices, one can derive the WTP of the consumers. However, such revealed preference methods require sufficiently liquid markets for the good or service in question in order to obtain the necessary data on actual consumer behavior. In the case of hydrogen-based transportation, markets with sufficient liquidity for such analyses are yet to be formed. On the other hand, analysts can use stated preference-based methods to study WTP. Particularly for goods or services where liquid markets are yet to be formed, as in this instance, such methods are the most frequently used. Among these methods are the so-called discrete choice experiments (DCE). Here, surveys are used where respondents chose their favorite option out of a set of alternative choices where different attributes (e.g., CO_2 emissions, refueling time, etc.) vary. Of these choices, analysts can derive the WTP for the good or service in question through the choices of the respondents.

For consumers to choose hydrogen-based transportation services over the available alternatives (i.e., fossil-fueled ones), its individual net utility must be the higher of the two. Currently, the TCO of hydrogen-based transportation exceeds the TCO of alternatives employing other fuels. In this case, either the WTP for hydrogen-based transportation must substantially exceed the WTP for fossil-based forms (i.e., because consumers are willing to pay more for environmentally friendlier transportation) or the TCO of hydrogen-based transportation must be substantially decreased until it is about on par with fossil-based alternatives. In either case, state regulation could lead to a situation in which the net utility of hydrogen-based transportation is maximal either by increasing net utility for hydrogen-based transportation (e.g., through subsidies) or by decreasing the net utility of fossil-fueled alternatives (e.g., through taxes). In accordance with the aforementioned observations (see Hydrogen Policy and Regulation section), a successful reduction in CO_2 emissions will require a balanced mix of these two measures.

A representative survey by Zimmer (2013a) for Germany indicates that about 83% of the population would be willing to spend about 5000 EUR more for environmentally friendlier alternatives. Translating the results of this study into TCO, environmentally friendlier mobility can exceed the TCO of fossil-fueled transportation but only by about 5000 EUR in the German case. Figure 4.9 illustrates some further results from studies on WTP for transportation. It indicates that WTP may vary greatly depending on location (country) and other characteristics (e.g., environmental concerns, refueling time, and the

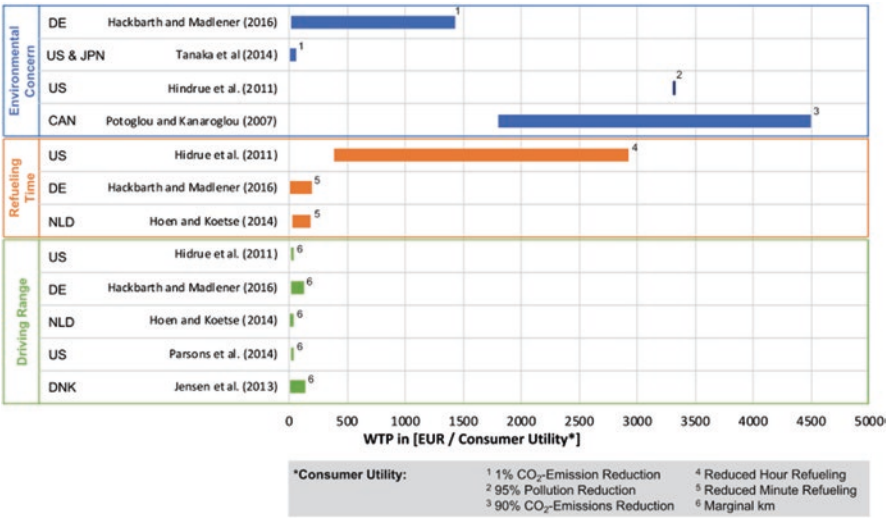


Fig. 4.9 Study results of the willingness to pay for different user aspects (Hackbarth and Madlener 2016; Tanaka et al. 2014; Hidrue et al. 2011; Hoen and Koetse 2014; Parsons et al. 2014; Jensen et al. 2013; Potoglou and Kanaroglou 2007)

driving range). According to the results, customers are willing to pay more for an alternative-fueled vehicle with reduced CO_2 emissions. Both FCEVs and BEVs might meet these requirements. However, compared to BEVs, FCEVs can offer the customer a higher degree of pain flexibility through a faster refueling process of only a few minutes, resulting in a driving range of several hundred kilometers. Although most average daily journeys are well below the range of BEVs, this flexibility remains an important criterion for vehicle purchases. Figure 4.9 shows that this directly translates into a higher WTP.

6 Conclusions

Hydrogen is a versatile energy carrier that offers numerous possibilities to decarbonize various sectors of the economy. To date, hydrogen has been used on an industrial scale worldwide but has been produced almost entirely from natural gas or coal. Hydrogen production from low-carbon energy resources is still costly, but its costs are expected to decline rapidly due to the falling costs of renewable energy and to realizing economies of scale and economies of mass production for electrolyzers (Dodds 2015). Green hydrogen is favorably received by the public and is less hazardous than fossil fuels, thus providing beneficial conditions for the technology's acceptance. Furthermore, many prospective consumers express a positive willingness-to-pay for green hydrogen services, which further reduces the utility gap for the adoption of hydrogen technologies. For these reasons, green hydrogen market entry and commercialization is receiving increasing attention from policymakers and businesses alike.

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