20 December 2024

Guideline:

Building up Hydrogen Refueling Stations in the Baltic Sea Region

Addressed to public authorities and pilot projects

This document has been developed by the Reiner Lemoine Institut within the Interreg project HyTruck.

The project HyTruck is supported by the Interreg Baltic Sea Region Programme 2021-2027

Content

List of Figures

List of Tables

List of abbreviations

AFIR	Alternative Fuels Infrastructure Regulation
AHP	Analytic Hierarchy Process
BEV	Battery Electric Vehicle
BSR	Baltic Sea Region
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CH_4	Methane
CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide equivalents
CVD	Clean Vehicles Directive
EHB	European Hydrogen Backbone
EU	European Union
FCEV	Fuel Cell Electric Vehicle
GET	Global Energy Transition
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GWP	Global Warming Potential
H_2	Hydrogen
HRS	Hydrogen Refueling Station
ICE	Internal Combustion Engine
ICET	Internal Combustion Engine Truck
ICEV	Internal Combustion Engine Vehicles
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MCDM	Multi-Criteria Decision Making
N2	Truck class 2 (German: Nutzfahrzeug Klasse): having a maximum mass exceeding 3.5 tonnes but not exceeding 12 tonnes
N_2O	Nitrous Oxide
N3	Truck class 3 (German: Nutzfahrzeug Klasse): having a maximum mass exceeding 12 tonnes
OSM	Open Street Map
P2X	Power2X
PEC	Photoelectrochemical
PEM	Proton Exchange Membrane
POX	Partial Oxidation of Natural Gas
PV	Photovoltaic
RED	Renewable Energy Directive
SMR	Steam Methane Reforming
SSP	Shared Socioeconomic Pathways
TAM	Total Addressable Market
TCO	Total Cost of Ownership
TEA	Techno-economic Analysis
TEN-T	Trans-European Transport Network
TRL	Technology Readiness Level

	Name	To Do	Guideline Chapter	
Introduction	Understanding	Understand hydrogen and the hydrogen value chain.	1, 2	☐
	Prework	Gather all previous work in the field of hydrogen, renewable energies, and mobility transformation at the regional and national levels.	1, 2, 3	☐
	Renewable hydrogen	Understand the basic idea of renewable hydrogen and why it's important.	2	☐
Concept	local stakeholder	Gather information about local stakeholders in the field of hydrogen and find out about their activities.	10	☐
	Demand forecast	Do the demand forecast for the next years (10 to 20) according to the chapter and the information you gathered.	3, 6	☐
	Different HRS concepts	Understand the differences and advantages between all the HRS design options and their equipment.	5	☐
	Choose HRS Concept	Decide based on the economic, ecologic and feasibility options on one of the designs	5, 6, 8	☐
	Understanding technical standards	Look at the technical standards for your HRS concept.	5	☐
Design	Find location	Find a location based on the requirements of your concept.	8	☐
	Create a network	Find collaborators and stakeholders.	10	☐
	Economic forecast	Look at investment and maintenance costs based on an annual level.	6	☐
	Collaboration	Receive LOIs and fixed supply agreements with local fleet operators.	10	☐
	Permits	Get a permit to build HRS.	9	☐
	Look at funding schemes for HRS	Get an understanding of how and where to apply for your project to receive funding from national credit agencies.	9	☐
	Credit and investment	Secure credit based on demand forecast, economic forecast and local collaborations. Take credit conditions into account for economic forecast.	3, 6	☐
	Start tendering	Understand the essence of the tendering procedure and the main elements of a tender document.	109	☐
	Registration	Register the HRS in Networks so customers can find the location easily.	9	☐

Introduction

This guideline was made to support public authorities in the process of building up Hydrogen Refueling Stations (HRS). It also addresses the building up of a transnational network of refueling stations. There will be information and decision-making support on the need for hydrogen, site selection and hydrogen demand for trucks. Additionally, it contains environmental considerations, information on hydrogen distribution, the design of an HRS, permits and regulations, economic considerations as well as networking and collaboration material.

Guideline scope

The Guideline is intended to be part of the earlier steps of the HyTruck project, to assist public authorities in their reflection on how to build the best hydrogen refueling stations. The rationale behind this document is that public authorities may benefit from following the advice in the Guidelines, as they are designing their HRS. Therefore, the Guideline should be used before the building, development and testing of HRS projects, and rather in the design phase and conception phase, in order to make the right decisions before starting to work the terrain. The following waterfall chart displays in which capacity the Guideline was designed and at which stage of a project it should be used by public authorities when building a hydrogen refueling station.

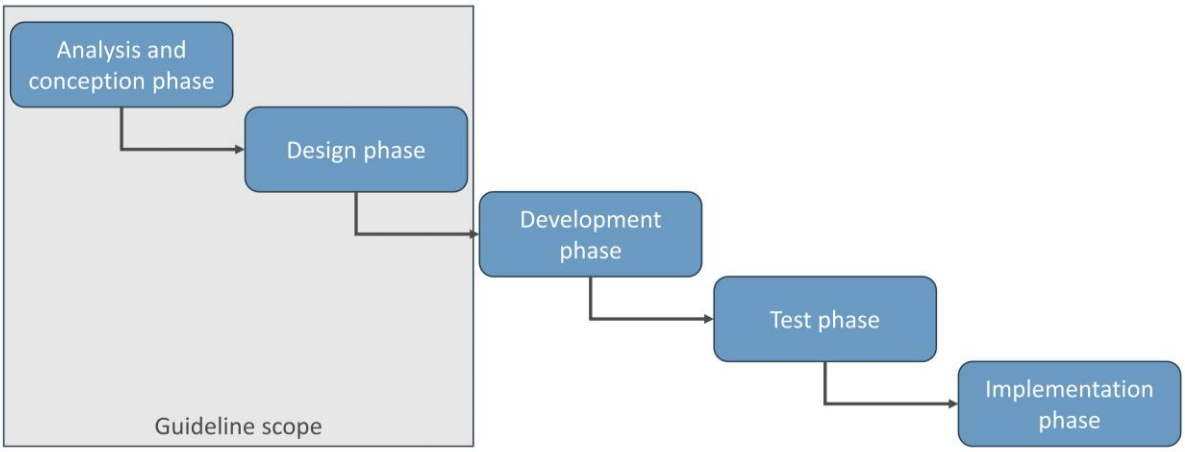

Figure 1: Scope of the Guideline

How to use the guideline

The guideline is divided into ten chapters. Each chapter answers specific questions public authorities might have regarding HRSs. The Guideline is split in three major parts.

Introduction: This part focuses on building up an understanding of hydrogen, it's use cases in different sectors and why it is important.

Concept: The second part focuses on different HRS concepts and looks into the benefits and disadvantages of these concepts. The goal is to find the most suitable concept for the region.

Design: This part takes a closer look in the first stages of planning HRS. It provides tools for site selection and gives information on permits and regulations and possible collaboration partners.

The subsequent picture shows an overview of the chapters.

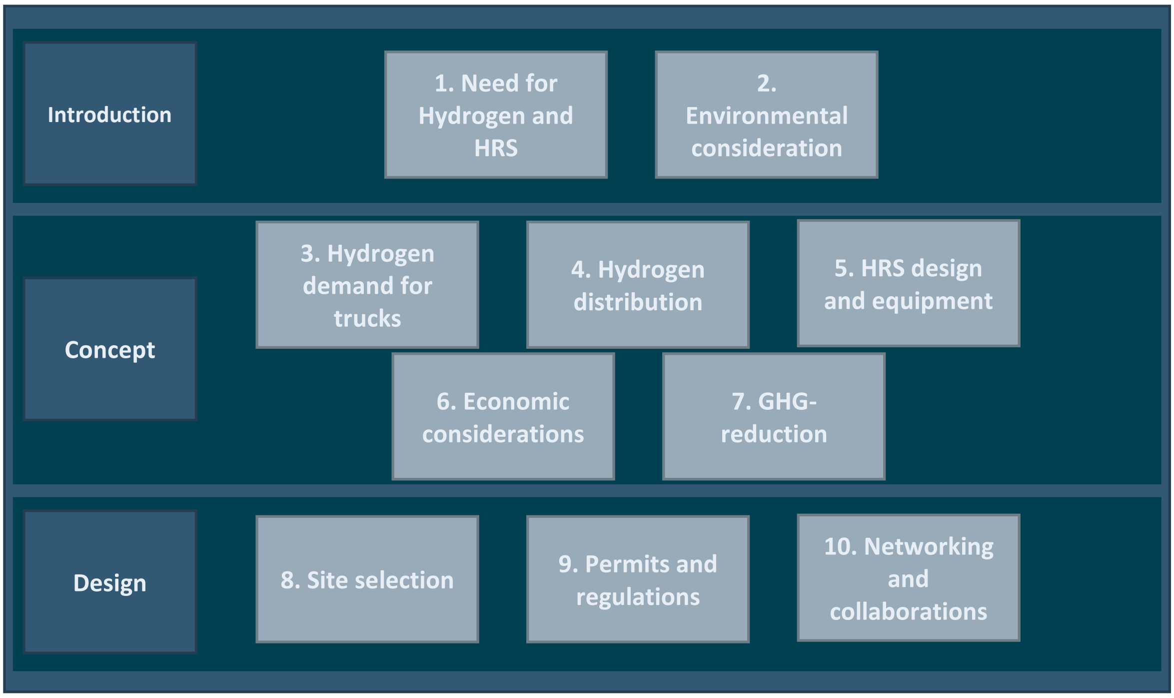

Figure 2: Structure and Goals of the Guideline

Interreg Project: HyTruck

The objective of the HyTruck project, funded by Interreg Baltic Sea Region (BSR), is to support public authorities in steering the development of a transnational network of hydrogen refueling stations (HRS) for trucks. This project aims to address the "chicken & egg problem" confronting hydrogen infrastructure, which both truck operators and infrastructure providers grapple with. On one hand, haulage and logistics companies with extensive fleets are eager to invest in fuel cell trucks to make their fleets more environmentally friendly. Nevertheless, for a fuel cell truck to travel from Rostock to Tartu (and back), it must have the ability to refuel with hydrogen along the way. On the other hand, HRS operators need assurance that their investments in fuel stations will be profitable. Without a clear expectation of sufficient demand, the infrastructure won't be established.

Presently, there is a lack of a cohesive HRS network for large trucks in the European Union. This challenge needs to be addressed by public authorities. They can support and steer the ramp-up of HRS infrastructure. Recent European legislation mandates their involvement in this regard. Establishing a cross-border HRS network is a multifaceted endeavor, involving considerations of spatial planning, economics, environmental impact, and technology. Ultimately, HyTruck is committed to the overarching objective of realizing emissions-free international road freight transport within the BSR.

The HyTruck project brings together partners from all BSR member states. The collaborative development of this guideline was a dynamic, iterative process, involving active participation from all project partners (see Figure 3). Initially, research institutions and industry partners joined forces to create a preliminary draft guideline document. This draft underwent practical testing by five pilot regions located along the TEN-T corridor. These pilot regions integrated the guideline into their own planning procedures, offering valuable insights into its practical application. The result is a standalone product that can benefit all regions seeking to accelerate the expansion of their hydrogen refueling infrastructure.

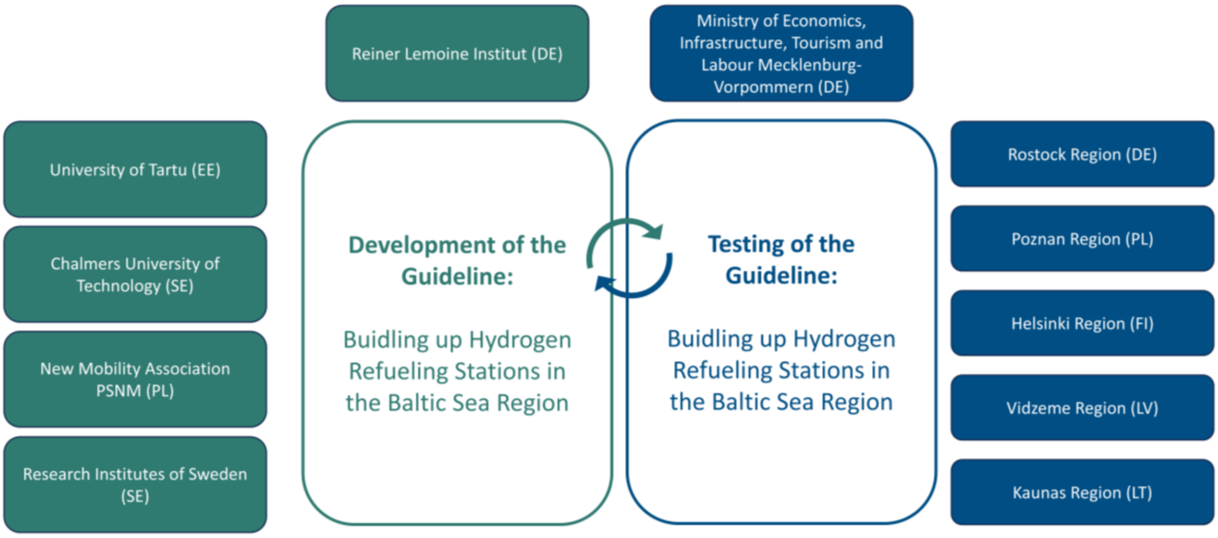

Figure 3: Development of the HRS Planning Guideline by the HyTruck Project

1. Need for hydrogen and HRSs

Global warming is one of the most urgent challenges.

The Intergovernmental Panel on Climate Change (IPCC) has warned that global warming is one of the most urgent challenges for societies in the 21st century. The latest IPCC report gathers scientific evidence supporting the claim that human-linked emissions are significantly contributing to climate change[1]. The continuous emissions of greenhouse gas (GHG) including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other substances are predicted to drive climate change causing adverse effects, such as:

Rising temperatures: Linked to heatwaves, changing weather patterns, and the melting of glaciers and ice caps.

Sea-level rise: The melting of polar ice caps causes sea levels to rise leading to coastal flooding and erosion.

Ocean acidification: Increased levels of CO_2 in the atmosphere are absorbed by the ocean, leading to more acidic waters and disastrous effects on marine life.

Extreme weather events: Climate change can contribute to more frequent and severe hurricanes, floods, wildfires, and droughts.

Economic impacts and security risks: Forced migration and conflict are consequences of resource scarcity, loss of coastal areas, reduced agricultural productivity, and extreme weather effects. In the economic field, there are concerns related to the damage to infrastructures and insurance claims.

As a result of human activities, the presence of GHG in the atmosphere has been increasing since the Industrial Revolution, see Figure 4.

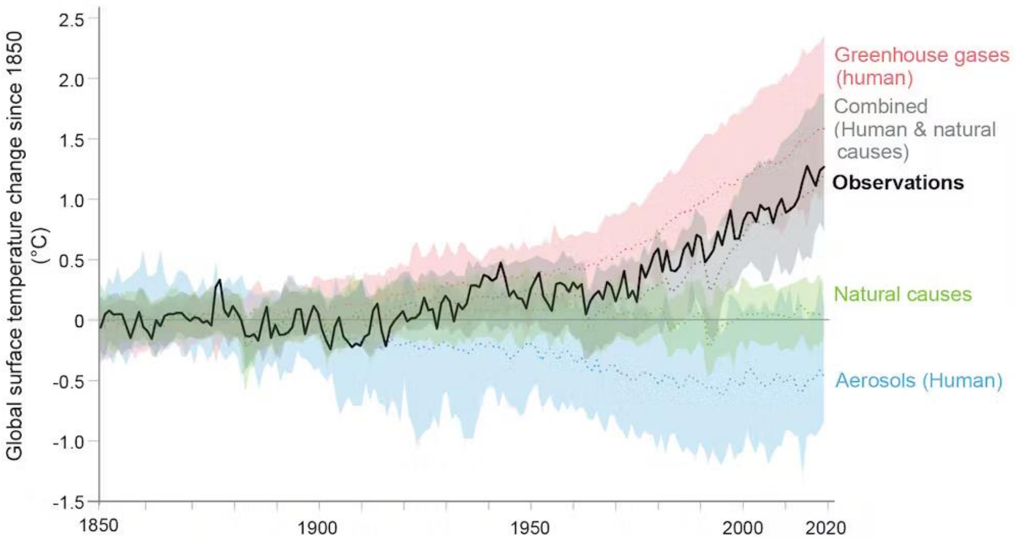

Figure 4: The Global Surface Temperature has changed since 1850 due to different causes, as presented in the IPCC sixth assessment report.

[1] Intergovernmental Panel On Climate Change (Ipcc), „Climate Change 2022 – Impacts, Adaptation and Vulnerability“.

Thus, mounting evidence suggests that taking action to decarbonize the transport sector is crucial to prevent the worst effects of global warming and to protect economic stability, environmental sustainability, energy security, and social stability in the long term. Quick and decisive action from governments is required to promote low and zero-carbon alternatives based on renewable resources. However, investment of resources should recognize the specificities and challenges of every sector and consider the potential of diverse areas to attend to energy demand. Green hydrogen (also known as "renewable" hydrogen, both terms being interchangeable in this document) ranks among the most promising of these zero-carbon alternatives, notably for the transport sector, although electrification is also seriously considered in this field.

Technological competition with battery-electric trucks

Hydrogen (H_2) has long been considered an alternative to fossil fuels as energy carriers in several economic sectors, including road transport. H_2 can be used to power light-duty and heavy-duty vehicles with onboard fuel cells or even combustion engines. Fuel cell electric vehicles (FCEV) have a higher energy conversion efficiency compared to conventional internal combustion engine vehicles (ICEV) while producing no pollutant emissions of fossil origin. Furthermore, FCEVs as well as battery electric vehicles (BEV) display zero tailpipe emissions while electric motors are highly efficient. Both technologies have their advantages and disadvantages as the subsequent table shows.

Table 1: Comparison of BEV and FCEV[2]

Aspect	BEV	FCEV
Total cost of ownership (TCO)	Low, soon lower than Diesel	High
Maximum range	800 km	1200 km
Refueling time	60 minutes	10-20 minutes
Economy of scale with cars	High	Low

FCEVs are more expensive but have a higher range and shorter refueling times. This is highly valuable for logistics companies with high time pressure. However, the usage of hydrogen trucks depends a lot on a well-developed network of HRSs.

From an energy security perspective, some drivers for deploying cleaner vehicle technologies are the enhancement of energy security by reducing dependence on fossil fuels and the diversification of energy sources. Moreover, from an environmental perspective, the main drivers are the improvement in air quality and the reduction in GHG emissions since diesel and gasoline-powered vehicles are a significant source of fossil CO_2 emissions as well as emissions

[2] Transport&Environment, „Comparison of hydrogen and battery electric trucks".

affecting human health. In fact, in 2018 transport was estimated to be responsible for about one-quarter of all energy-related GHG emissions, and about 72% of this was attributed to road transport[3].

No ramp-up without infrastructure

Currently, maintaining a fleet of FCEVs involves high costs and thus uncertainty regarding the economic viability of the sector, discouraging investments. However, business operations of haulage companies necessitate a well-designed, dense enough transnational network of refueling stations. The higher the quality and reliability of the network, the more will stakeholders consider hydrogen a viable alternative.

The high fixed costs associated with maintaining an HRS imply that such stations cannot be profitable unless serving a large enough number of customers. Hence, the installation of refueling stations currently is not interesting for private investors. Therefore, it is vital for the further deployment of FCEVs that public authorities step in and invest in public hydrogen refueling stations before private investors can see a profitable opportunity and contribute to a large-scale development of stations.

The all-rounder hydrogen

Hydrogen is considered the multi-talent of the energy transition. Today, 95 percent of the global hydrogen is produced from fossil natural gas, from coal, or – as a by-product – from oil[4]. In the future, hydrogen is intended to be produced from water using electrolysis and renewable energy sources. This results in so-called "green" hydrogen, which is GHG-neutral (see Chapter Environmental consideration). It contributes to the decarbonization of established applications, like providing feedstock for the chemical industry. Moreover, it aids in emissions reduction and promotes sector integration across industry, energy, transportation, and heating. However, it is crucial to recognize that a considerable amount of energy is lost during the production of renewable hydrogen. Therefore, it is essential to strategically assess the areas where hydrogen applications offer the greatest benefits. renewable hydrogen holds particular significance in applications where hydrogen serves as a feedstock or is required for applications involving exceptionally high temperatures and/or high energy densities. Figure 5 gives an overview of the most relevant hydrogen applications and names potential alternatives for decarbonization. The International Renewable Energy Agency (IRENA) gives an overview of the prioritization of hydrogen applications (see[5]).

[3] International Energy Agency (IEA), „Energy Consumption in Road Transport in Selected IEA Countries, 2000-2018 – Charts – Data & Statistics".
[4] IRENA, „Geopolitics of the Energy Transformation: The Hydrogen Factor".
[5] IRENA, „Hydrogen: Overview".

As a feedstock, hydrogen plays an important role in the industrial sector. As Figure 5 shows hydrogen is a high-priority resource for the chemical industry and steel production due to the lack of potential alternatives in these sectors. Besides, hydrogen has the potential to be used as an energy carrier in cement, glass, and paper production. Those production lines that require high temperatures are well suited for the use of hydrogen and electrification is rarely developed as an alternative. The heat demand in the paper industry, however, is not very high, so electrification and biomass are alternatives in current use and are already established.

In the transportation sector, hydrogen assumes a critical role, particularly in the creation of sustainable fuels for aviation and shipping. Hydrogen derivatives like ammonia, methanol, and synthetic kerosene play an important role in decarbonizing so-called hard-to-abate applications. These fuels are the only options for shipping and aviation, where there are only early experiments with electric motors for short-distance travel. For long-haul road transport, hydrogen is part of the solution, too. This is because hydrogen fuel cell vehicles become a more viable option compared to alternative grid or battery electrification technologies as the distance and weight of the vehicle and load increase. As a result, the use of E-fuels in automobiles provides only a short-term benefit for residual vehicles.

In the power sector, hydrogen-fuelled gas turbines will play a critical role in the future energy system, particularly for providing electricity and mid-temperature heat during periods of low renewable energy generation. Hydrogen is used as a seasonal storage solution in this context. For shorter gaps, direct electrical alternatives can also be used. In contrast, hydrogen has a very low priority in the heating sector, where there are numerous alternatives for heating homes.

Given hydrogen's pivotal role in the energy transition, it is imperative to approach hydrogen infrastructure development from a holistic perspective. The planning processes for hydrogen refueling stations (HRS) have the potential to create synergies with the energy sector, such as utilizing electrolyzers for power storage. Additionally, opportunities for collaboration can be found in other hydrogen applications within the transportation sector, such as establishing multi-fuel hubs at ports or airports, as well as extending into sectors beyond transportation, such as fertilizer production. Consequently, when strategizing HRS deployment, it is advisable to take a comprehensive approach that goes beyond considering hydrogen's sole application in transportation.

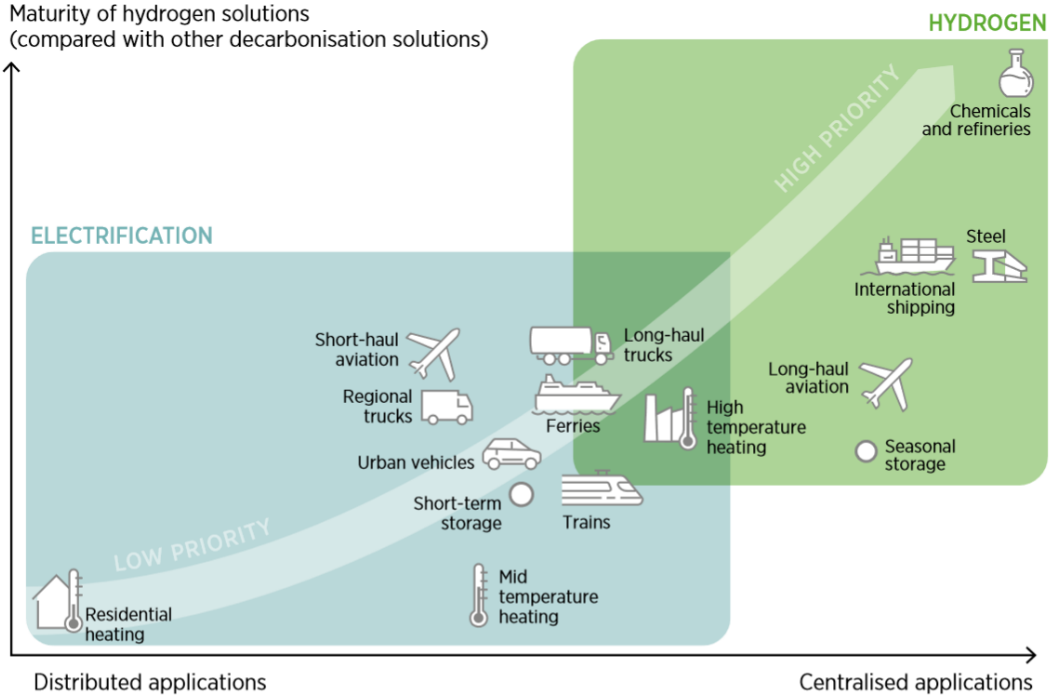

Figure 5: Prioritization of Hydrogen Applications according to IRENA

The value chain of renewable hydrogen

The value chain of renewable hydrogen is a comprehensive ecosystem that is fundamentally linked to the use of renewable energy sources such as solar, wind, or hydroelectric power. These sources are essential to power the electrolysis process, where water is split into hydrogen and oxygen, thereby producing renewable hydrogen. By contrast, the electrolysis can be powered by electricity generated by conventional energy sources, producing “blue” or “grey” hydrogen, which are not as interesting – or even harmful – in the context of the decarbonization of the economy. The production of such renewable hydrogen involves the chemical process of water electrolysis, which often takes place near renewable energy production sites to minimize energy loss and contamination of the hydrogen during its transportation. Once produced, the hydrogen must be transported and distributed, which can be challenging due to its high flammability and low density. This stage may involve pipelines, dedicated trailers, or even ships equipped to handle hydrogen safely. The use of renewable hydrogen is diverse, ranging from fueling heavier vehicles, like trucks, buses, and cars, to industrial applications such as steel production or chemical and fertilizers manufacturing, where it serves as both a feedstock and a clean source of energy. The network of actors and stakeholders in this value chain includes renewable energy producers such as PV and windfarm operators, technology developers, transportation and distribution companies, industrial end-users, policymakers, and regulatory bodies. Each plays a critical role in developing infrastructure, setting safety and efficiency standards, and driving widespread adoption of the technology through policies like financial incentives and funding scheme. Such synergies contribute to coordinating efforts towards a sustainable energy future.

2. Environmental consideration

The colors of a colorless element

As a clean and versatile energy carrier, hydrogen has gained widespread attention for its potential to drive a cleaner energy future, particularly in the context of decarbonizing various sectors. Despite its inherent colourlessness, the differentiation of hydrogen by colors have become essential in evaluating the sustainability of various hydrogen production methods and facilitating the transition to a low-carbon energy system[6]. This color spectrum includes so-called grey, blue, green ("renewable"), brown, black, turquoise, pink, yellow and white hydrogen (Table 2) and is evolving and expanding over time.

Steam Methane Reforming (SMR) is a widely used industrial process for the production of hydrogen, accounting for the majority of global hydrogen output. This process involves the reaction between steam and methane (the primary component of natural gas) in the presence of a catalyst to produce H_2, carbon monoxide (CO), and CO_2. While efficient, SMR produces significant GHG emissions, making it a major contributor to carbon footprints. Grey hydrogen refers to hydrogen produced from SMR with the resulting CO_2 being directly released into the atmosphere without any capture[7].

Blue hydrogen involves the use of SMR with carbon capture and storage (CCS) technology to reduce carbon emissions. While a significant portion of the produced CO_2 is captured (up to 72% – 96%) and stored underground, some CO_2 remains untrapped[8].

Renewable hydrogen is hydrogen produced without generating any CO_2 emissions. It is generated through the electrolysis of water using renewable energy sources like wind and solar power, thus producing no CO_2 emissions[9]. Note that European law excludes electricity generated by nuclear power from this definition. This implies that renewable hydrogen cannot be produced with electricity generated by nuclear plants, despite its very low carbon generation ratio.[10]

---

[6] Nationalgrid, „The Hydrogen Colour Spectrum"; Umweltbundesamt, „Welche Treibhausgasemissionen verursacht die Wasserstoffproduktion?"
[7] Umweltbundesamt, „Welche Treibhausgasemissionen verursacht die Wasserstoffproduktion?"
[8] Umweltbundesamt.
[9] Shiva Kumar and Lim, „An Overview of Water Electrolysis Technologies for Green Hydrogen Production".
[10] European Council, European Parliament, „Renewable Energy Directive II".

Table 2: Hydrogen colour spectrum

Colour	Process	Energy source	Products	CO_2 emissions[a]
Green	Electrolysis	Renewable energy	$H_2 + O_2$	12,5-50,0 g CO_2/MJ H_2
Blue	SMR + CCS	Natural gas	$H_2 + CO_2 + CO$	102,9-108,8 g CO_2/MJ H_2
Grey	Steam Reforming	Natural gas	$H_2 + CO_2 + CO$	128,5-134,2 g CO_2/MJ H_2

Source: Umweltbundesamt

[a] Calculations were made based on the heating value of methane and hydrogen. Data includes natural gas production and processing, hydrogen production, CCS, hydrogen transportation, natural gas transportation, process energy and CO2 transportation.

The primary motivation for using hydrogen lies in its potential to reduce GHG emissions. Nevertheless, the extent of GHG emissions reduction depends on several factors, including the method of hydrogen production, transportation distance, leakage rates, and various other considerations.

For a comprehensive assessment of environmental impacts, a life cycle assessment analysis proves to be the most effective approach. This method encompasses the examination of all emissions generated by the fuel throughout its entire lifecycle, encompassing energy production, potential refining processes, transportation, and its ultimate usage phase.

Besides GHG emissions other environmental impacts should be considered as well.

3. Hydrogen Demand for Trucks

Analyzing the current and expected demand for hydrogen-powered vehicles within the planned region is a fundamental step to ensure the long-term viability of the proposed fuel station. To facilitate this analysis, the following considerations should be considered:

Identify target applications: Determine the specific applications and use cases where hydrogen-powered trucks are most suitable. Consider applications beyond road transport, such as aviation, shipping, remote trains, industrial usage, and the power sector. Evaluate which applications are most relevant and feasible for your region.

Fleet analysis: Assess the size and composition of truck fleets operating within your region. Identify potential early adopters of hydrogen technology and understand their fleet replacement cycles. Engage in discussions with fleet operators to gain insights into their decarbonization strategies. Additionally, utilize open data sets to explore the potential for hydrogen adoption within the region.

Total Addressable Market (TAM): Calculate the TAM for hydrogen-powered trucks by considering the number of trucks in your target market, their annual mileage, and the potential percentage of trucks that could transition to hydrogen.

To gain insights into customer demand, it is beneficial to explore international data sources related to European road freight transport flows, registered trucks, and potential growth scenarios.

Growth projections: Consider scientific and industry growth projections and forecasts for hydrogen-powered trucks, which can provide insights into future demand trends. Explore scenarios provided by the HyTruck project to assess potential growth trajectories.

Existing infrastructure: Evaluate the availability and accessibility of existing hydrogen refueling stations within your region. Understanding the current infrastructure landscape will help in identifying any gaps or opportunities for expanding the refueling network. Also, take a look at the existing infrastructure for fossil fuels. With growth projections in FCEVs, a hydrogen demand can be assumed.

Political aims and strategies: Evaluate your national/regional strategies for GHG-reduction or hydrogen. The goals within these strategies can guide in planning regional hydrogen demand.

The market of fuel cell trucks

Understanding the current technology used in fuel cell trucks is important when planning HRS. It's not just about tracking market trends but also about understanding the specific technological requirements of the vehicles themselves. This knowledge is crucial because it guides HRS planners in determining what infrastructure and equipment need to be integrated to support the existing and future technologies efficiently.

Table 3 Current models of fuel cell trucks

Vehicle Model	Vehicle Type	Total Weight [t]	Tank Pressure [bar]	Tank Volume [kg]	Chemical phase	Range [km]	Availability
Esoro[11]	Box Truck	35	350	31	gas	400	2017
Hyundai Xcient Fuel Cell[12]	Box Truck	18	350	31	gas	400	2020
Paul Nutzfahrzeuge Ph2P[13]	Semi-Truck	24	350	30	gas	450	2022
Hyzon Motors HyMaxSeries[14]	Semi-Truck	24	350	30	gas	400	2023
	Semi-Truck	46	350	50 - 60	gas	680	2023
	Semi-Truck	70	350	50 - 60	gas	600	2023
Enginius (Faun group) CITYPOWER[15]	Box Truck	16	700	32	gas	500	2023
Quantron QHM FCEV 44-1000[16]	Semi-Truck	40	700	54	gas	700	2023
Zepp.solutions[17]	Semi-Truck	40	350	50	gas	700	2023
Nicola /Iveco[18]	Semi-Truck	40	700	70	gas	805	2024
Daimler GenH2[19]	Semi-Truck		350	80	liquid	1000	2024
Quantron QHM FCEV AERO 65-900 / 65-2000[20]	Semi-Truck	44, 50, 65	700	48-116	gas	500 / 1400	2024
Zepp.solutions[21]	Semi-Truck	40	700	80	gas	1000	2024

[11] Esoro, „Weltweit erster Wasserstoff-LKW mit Anhänger, der die LKW-Anforderungen für die Coop-Logistik erfüllen kann“.
[12] Hyundai, „XCIENT Fuel Cell“.
[13] Paul Nutzfahrzeuge, „PH2P Truck“.
[14] Hyzon, „Hyzon Hymax Series“.
[15] Enginius, „FACTSHEET – ENGINIUS“.
[16] Quantron, „Q-Heavy Quantron“.
[17] zepp.solutions, „New Hydrogen-Powered Truck: ‚Europa‘ to Launch in Q4 2023“.
[18] Gomoll, „Brennstoffzellen-Truck im Anmarsch: So fährt sich der Nikola Tre FCEV“.
[19] Daimler truck, „Entwicklungsmeilenstein erreicht: Daimler Truck testet Brennstoffzellen-Lkw mit Flüssigwasserstoff“.
[20] Quantron, „Q-Heavy Quantron“.
[21] zepp.solutions, „New Hydrogen-Powered Truck: ‚Europa‘ to Launch in Q4 2023“.

Total minimum capacity of the HRSs in the BSR[22]

The total number of hydrogen refueling stations along the TEN-T core network corridor in the HyTruck Member States needed to meet the AFIR targets is a minimum of 170 (based on the analysis of route lengths and the number of 200 km sections of the core TEN-T network). The combined capacity of these stations should be 85 – 170 t/day. This number is based on the requirement of accessibility of hydrogen refueling station with a planned total capacity of >= 1t/day, according to AFIR requirements. If the HRS is located in a low-frequented area, the maximum capacity can be reduced to 0,5 t/day. For the BSR-Region, the requirements per country are stated in Table 4.

Table 4 Minimum Number of Refueling Station per BSR country (Calculations based on the TEN-T length per country)

	Core TEN-T length (km)	Minimum number of HRS (both direction)	Combined minimum capacity of hydrogen of the stations
Estonia	481	6	3 - 6 t / day
Finland	1100	12	6 - 12 t / day
Germany	6365	64	32 - 64 t / day
Latvia	850	10	5 - 10 t / day
Lithuania	597	6	3 - 6 t / day
Poland	3812	40	20 - 40 t / day
Sweden	3012	32	16 - 32 t / day

[22] PSPA, „PSPA".

Projecting hydrogen demand

The goal of this chapter is to identify future hydrogen demand in the region to plan the size of an HRS. To do so, it is helpful to gather as many data points as possible. Therefore, get in touch with as many local fleet operators, take a look at regional and national strategies and legislation, as well as scientific growth forecasts. All the information can then be used for a demand forecast. Figure 6 shows an example of a demand forecast based on different information.

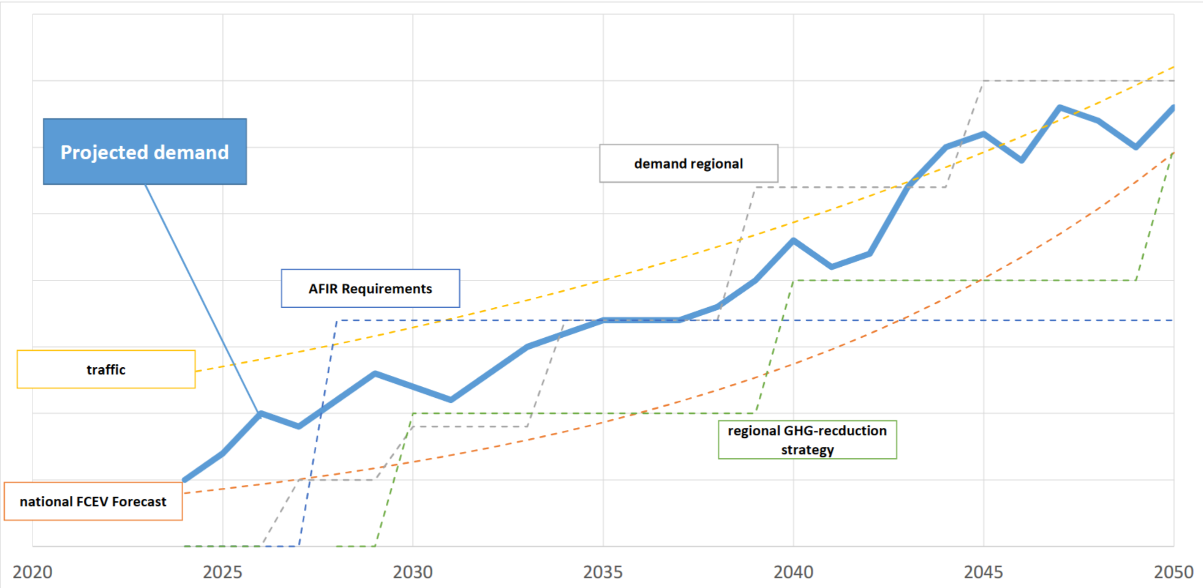

Figure 6: Demand Forecast based on Information such as Forecasts, Strategies, and Regional demand

4. Hydrogen distribution

An HRS in accordance with AFIR guidelines requires a minimum daily supply of one ton of hydrogen, although the actual daily demand could potentially be much higher based on hydrogen demand analysis. Various methods are available for delivering hydrogen to the fuel station to ensure a reliable supply. These options include utilizing trailers, on-site electrolysis, and hydrogen pipeline transport, which can also be combined if necessary (Overview distribution methods).

Once the hydrogen arrives at the fuel station, it must be adequately stored. In line with industrial standards, hydrogen gas is typically stored using pressure tanks. These tanks come in both low-pressure (up to 350 bar) and high-pressure (up to 1000 bar) variants to meet specific storage requirements (Overview storage methods).

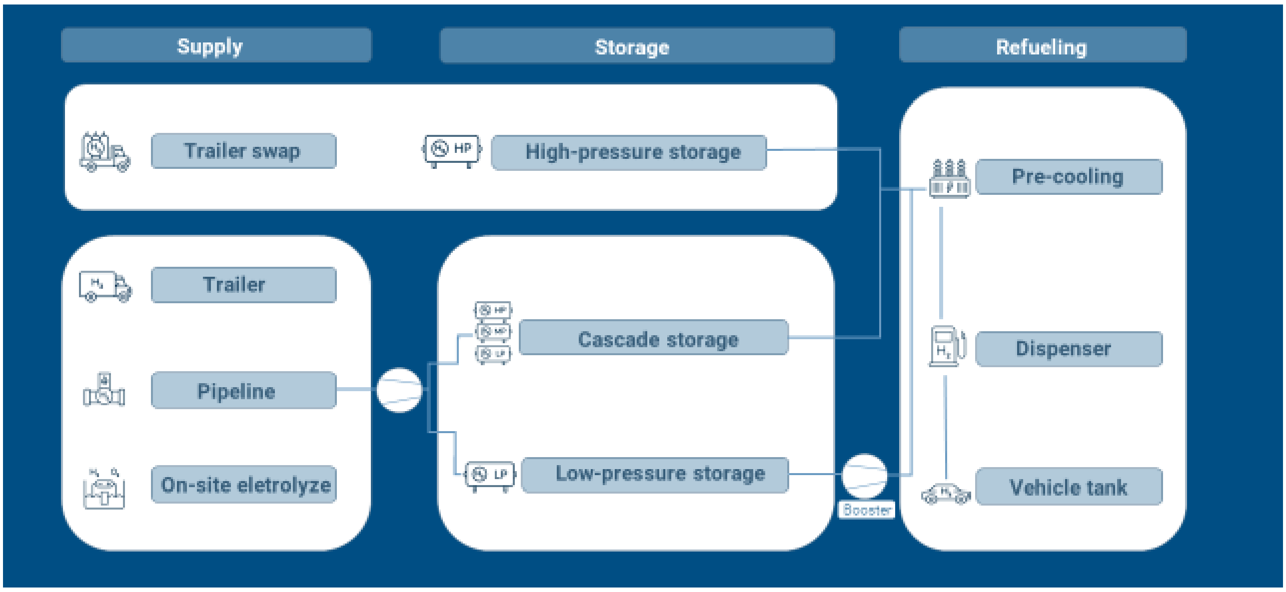

Figure 7: Layout of Hydrogen Refueling Stations

The overall goal of this chapter is to give an overview of different distribution and storage options, their advantages, and dependencies.

Overview distribution methods

Distribution enables the regional disconnection of energy generation and consumption. Therefore, it is the linkage between hydrogen production and demand sites.

On-/Near-site electrolysis

One option for having renewable hydrogen available for trucks is direct integration into the HRS (onsite production). The advantage of onsite electrolysis is that it is independent of any transport infrastructure. However, the demand for local storage capacity is higher. Locations with high wind potential and sufficient space for PV systems have favorable conditions. The sourcing of renewable energy is important to ensure the production of renewable hydrogen following Renewable Energy Directive (RED) II. Renewable energy installations and hydrogen production can complement each other well, as electrolyzers can be operated flexibly according to the availability of renewable resources.

One challenge with on-site hydrogen production is the fluctuation in output due to the intermittent nature of renewable energy sources. To ensure reliable on-site supply, cost-effective storage solutions capable of storing hydrogen for several days are essential (Overview storage methods). Onsite production offers the advantage of producing high-quality hydrogen without the need for expensive purification processes, thanks to modern proton exchange membrane (PEM) electrolyzers. In cases where local storage alone cannot bridge production gaps, considering supplementary hydrogen supply methods like truck trailers or pipelines, becomes a practical option.

Implementing on-site hydrogen production introduces significant complexities in terms of the business models, operational schemes, and site selection. When done right, on-site hydrogen production comes with several benefits. It enables cost-effective production of renewable hydrogen, which not only benefits the power grid but also allows for meeting hydrogen demand quickly, even in areas without nearby pipelines, and without the need for long transportation routes. On the other hand, on-site hydrogen production faces challenges in the HRS site selection, due to the needed access to water and renewable energies. The possibility of producing hydrogen on-site comes with higher challenges in the permit process and has higher investment costs compared to other supply options.

Note: In most of the cases the chain of action is the other way around. When a hydrogen production plant is being built for example to produce hydrogen for an industrial site, a refueling station sometimes is also implemented to expand the offer. Building a hydrogen production plant just to supply a refueling station is a rare case.

Trailer

For smaller quantities and shorter distances, gaseous hydrogen can be transported by road[23]. In practice, this is typically done over distances up to 200-300 km using multi-bottle bundles or large cylindrical tubes[24]. The tank trucks operate at pressures of 200 to 500 bar and can transport 500 to 1000 kg of hydrogen[25]. Using transport trailers with higher energy densities can reduce the supply frequency and, consequently, logistics costs while also minimizing space requirements at refueling stations[26]. For this reason, high-pressure trailers at 700 bar are under development, and there is consideration for potentially transporting hydrogen in liquid form. This could allow for the transportation of 4 tons of liquid hydrogen per delivery[27]. However, there are only two hydrogen liquefaction plants in the European Union (EU) at the moment[28]. Hydrogen liquefaction requires an industrial-scale plant and relies on a continuous hydrogen supply. It is therefore expensive. If there is a need for liquefied hydrogen, regional funding and infrastructure development will be required.

The investment costs for trucks and gas tanks amount to 840.000 €[29]. With a 40-foot trailer, up to 1100 kg of hydrogen can be transported[30]. The investment costs for liquid tanks and trucks for hydrogen transport are higher, totaling 1070000 €.

Pipeline

Pipelines are particularly suited for transporting large quantities of gaseous hydrogen. They transport gaseous low-pressure hydrogen commonly in steel pipes. At the EU level, a large-scale hydrogen backbone network is currently being planned - the European Hydrogen Backbone (EHB)[31]. European member states have additional networks and are integrating their plans into the EHB. The German core network e.g., scheduled to be completed by 2032, aims to connect industrial large-scale hydrogen consumers, power plant sites, and key production[32], import, and storage locations[33].

---

[23] Ehret, „Wasserstoffmobilität: Stand, Trends, Perspektiven“.
[24] dena, „STUDIE: Geschäftsmodelle für dezentrale Wasserstoffkonzepte – Zeit zum Nachsteuern“.
[25] Adolf u. a., „Energy of the Future? : Sustainable Mobility through Fuel Cells and H2 ; Shell Hydrogen Study“.
[26] NOW, „Marktentwicklung klimafreundlicher Technologien im schweren Straßengüterverkehr“.
[27] dena, „STUDIE: Geschäftsmodelle für dezentrale Wasserstoffkonzepte – Zeit zum Nachsteuern“.
[28] FuelCellsWorks, „Linde Holds Ground-Breaking Ceremony For New Hydrogen Liquefier In Leuna - FuelCellsWorks“.
[29] dena, „STUDIE: Geschäftsmodelle für dezentrale Wasserstoffkonzepte – Zeit zum Nachsteuern“.
[30] LBST und DLR, „H2-Infrastruktur für Nutzfahrzeuge im Fernverkehr Aktueller Entwicklungsstand und Perspektiven“.
[31] van Rossum u. a., „European Hydrogen Backbone“.
[32] Feed-in capacities of electrolyzers for hydrogen are uniformly scaled down to 50% per site. However, for electrolyzers that receive funding as IPCEI (approximately 2.5 GWel) or those that are funded as real-world laboratories of the energy transition (approximately 0.2 GWel), the full planned feed-in capacity (i.e., 100%) is used as the basis.
[33] Bundesministerium für Wirtschaft und Klimaschutz BMWK, „Pressemitteilung - Bundeskabinett beschließt Gesetzentwurf zur Schaffung eines Wasserstoff-Kernnetzes“.

In addition to centralized networks, hydrogen pipelines can serve as a decentralized transportation option at the local level, facilitating the connection of larger local consumers with regional production. Pipeline segments can be used not only for transportation but also for low-cost hydrogen storage. A pipeline with a diameter of 600 mm and a flow rate of about two tons per day costs 1,570 €/m[34] [35]. Costs and environmental impacts can be reduced by reusing existing natural gas pipelines for infrastructure development[36]. Though this approach saves infrastructure costs, it also requires costly additional purification steps (see

Contamination from transport and storage).

Pipelines provide a very reliable way of hydrogen supply for HRS. Due to the low availability of larger pipeline networks, the sites suitable for this supply method are limited. Thanks to economy of scale and mostly big production sites supplying pipeline networks the prices for hydrogen can be low and the reliable flow rate can make bigger storage containers obsolete.

[34] Rose, „Modeling a Potential Hydrogen Refueling Station Network for Fuel Cell Heavy-Duty Vehicles in Germany in 2050“.
[35] Krieg, *Konzept und Kosten eines Pipelinesystems zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff*.
[36] SRU, *Wasserstoff im Klimaschutz*.

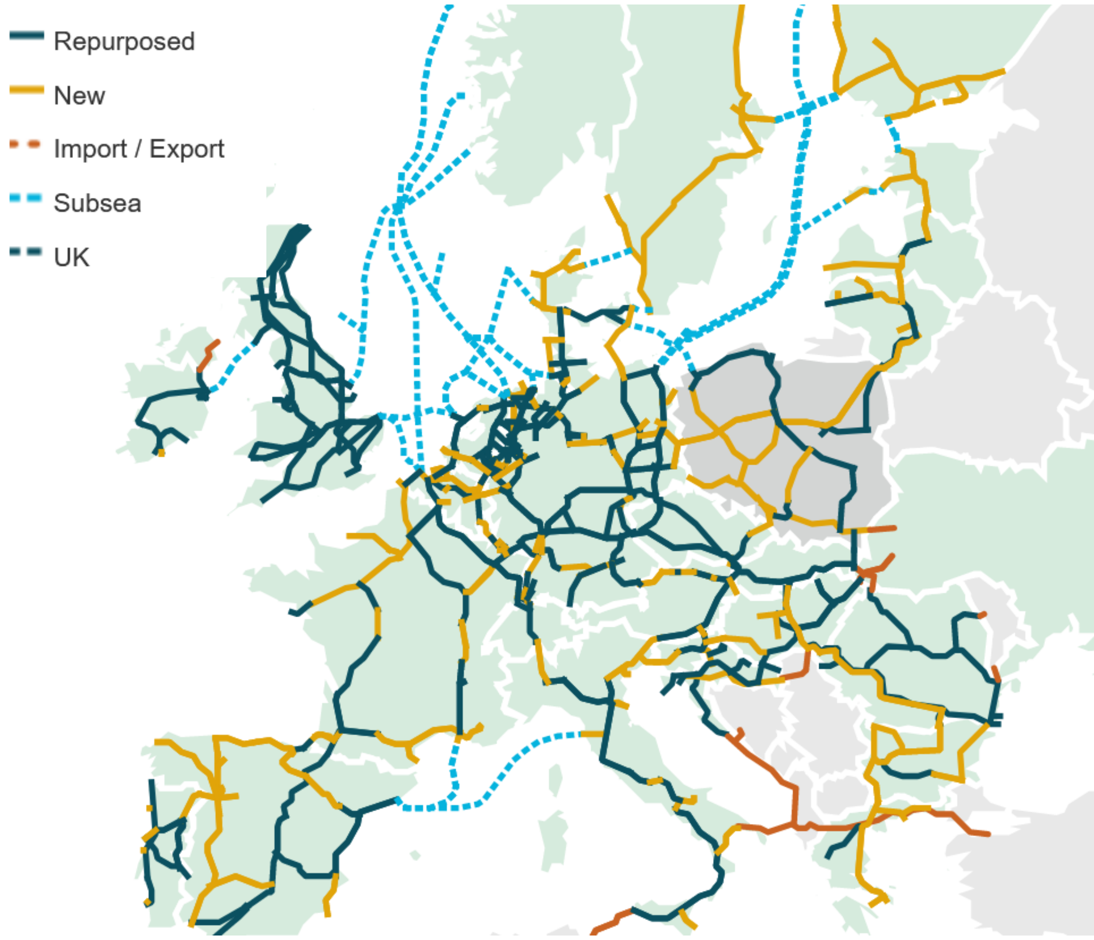

Figure 8: European Hydrogen Backbone[37]

Overview storage methods

Storage enables the temporal disconnection of energy generation and consumption. This can be important to ensure a consistent fulfillment of energy demands. In the following section, we look at the specifics of storage technology.

Table 5 offers a summary of different gas storage types along with their key features. These storage methods are currently the most commonly used at fuel stations.

Storage units for gaseous hydrogen at HRSs depend on the initial pressure from the electrolyzer (1-50 bar) and the dispensing pressure for heavy-duty transportation (350 and 700 bar)[38]. They include low, medium, and high-pressure storage (below 50 bar; 200 to 500 bar; 500 to 1000 bar), forming a multi-stage hydrogen storage system referred to as a pressure cascade. Hydrogen storage systems are categorized as Type I to Type IV.

[37] Guidehouse, „European Hydrogen Backbone Maps | EHB European Hydrogen Backbone“.
[38] LBST und DLR, „H2-Infrastruktur für Nutzfahrzeuge im Fernverkehr Aktueller Entwicklungsstand und Perspektiven“.

Table 5: Classification of Hydrogen Storage Tanks I to IV[39]

Gas Pressure Containers	Type I	Type II	Type III	Type IV
Pressure	Max. 200 bar	1000 bar	Typically 350 or 700 bar	Max. 1000 bar
Application	Application in the gas industry, stationary storage, and transport.	Stationary applications.	Standard in mobility, also suitable for stationary applications.	Application in transportation.
Material/Structure	Hollow body made of metal (steel).	Steel pressure vessel with fiber winding in the cylindrical area.	Inner liner made of metal and composite material.	Inner liner made of PE or PA, outer protective shell made of carbon fiber.
Load Capacity	Low	→	→	High
Cost	Low	→	→	High

Low-pressure gas containers (Type I) typically consist of simple cylindrical steel vessels, which can be either upright or horizontally installed. These storage units are the most cost-effective and are generally utilized as buffer storage[40]. Higher pressure requirements necessitate reinforced container construction, allowing for pressures up to 1000 bar[41]. However, the more complex design leads to higher storage costs. An adequately sized high-pressure storage unit offers the advantage of enabling rapid and complete refueling at 700 bar[42].

Hydrogen storage requires significant space, as demonstrated by the Iberdrola project in Puertollano, Spain. There, a hydrogen project for fertilizer production is currently being implemented. Eleven hydrogen tanks with a capacity of almost 30 tons of hydrogen are used to buffer the fluctuating yields of the PV-FFA coupled electrolysis[43]. Each tank has a length of 23 meters, a diameter of 2.5 meters, and a storage volume of 133 m^3. This allows the storage of approximately 2700 kg of hydrogen per tank. This illustrates that low-pressure storage

[39] Hy-NATuRe, „Hy-NATuRe - Zukunft gestalten mit Wasserstoff“.
[40] LBST und DLR, „H2-Infrastruktur für Nutzfahrzeuge im Fernverkehr Aktueller Entwicklungsstand und Perspektiven“.
[41] dena, „STUDIE: Geschäftsmodelle für dezentrale Wasserstoffkonzepte – Zeit zum Nachsteuern“.
[42] LBST und DLR, „H2-Infrastruktur für Nutzfahrzeuge im Fernverkehr Aktueller Entwicklungsstand und Perspektiven“.
[43] IBERDROLA, „The First 5 Green Hydrogen Storage Tanks Arrive in Puertollano“.

systems require a significant amount of space. In addition to the associated costs, this space requirement limits the potential storage capacity at filling stations. Storing more than 3 tons of hydrogen seems unrealistic in the context of space limitations at filling stations. It should also be noted that the amount of hydrogen stored determines the required permitting process. For example, quantities of up to 3 tons do not require an extensive approval process under the German Federal Immission Control Act (German: Bundes-Immissionsschutzgesetz)[44].

In addition to space limitations, the storage capacities for hydrogen are primarily constrained by costs. As seen in Table 5, the costs for storage increase with higher pressure levels.

Hydrogen storage can be either local fixed installations or mobile storage units. Mobile storage units offer the advantage of modular expansion according to capacity requirements. They also streamline trailer delivery of hydrogen, as the hydrogen to be stored can be conveniently parked or swapped at the HRS with the trailer (swap body)[45] [46]. As the capacities for heavy-duty transport are expected to be lower initially, the option of modular expansion as demand increases is appealing. It allows for smaller initial capacity sizing, thus reducing initial investment. This option requires the provision of suitable expansion land.

Cavern storage can also be used for hydrogen storage, offering the possibility of storing significant amounts of hydrogen underground. For example, former salt caverns could be repurposed for this use. They are relevant for regional networks with higher infrastructure requirements and are not suitable for local hydrogen storage at HRSs. Regarding heavy-duty transport, potential contamination from cavern storage also comes into play.

Contamination from transport and storage

The quality of hydrogen is closely tied to its purity and encompasses factors such as stability, consistency, and overall performance. Hydrogen purity is represented as a percentage, with the leading digit indicating the number of nines in the value. For instance, hydrogen 3.0 reflects a purity of 99.9 percent, while hydrogen 5.0 indicates a purity of 99.999 percent[47]. Impurities in hydrogen can stem from various sources, including the production process, storage, and transportation. Ensuring the high purity of hydrogen is essential to prevent potential contamination issues, maintain the integrity of industrial processes, and promote environmental sustainability. Guidelines such as DIN EN 17124:2022-12 define the criteria for

[44] NOW GmbH, „Genehmigungsleitfaden für H2-Tankstellen“.
[45] LBST und DLR, „H2-Infrastruktur für Nutzfahrzeuge im Fernverkehr Aktueller Entwicklungsstand und Perspektiven“.
[46] Wystrach, „WyCarrier Datenblatt“.
[47] EMCEL, „Reinheit von Wasserstoff: Wer nutzt welche Bezeichnung?“

the use of hydrogen in PEM-fuel cells, including limit values for certain impurities[48]. Compared to fuel cells, hydrogen engines generally require less purity[49].

Potential sources of unintended components in hydrogen can arise not only from the hydrogen production process itself but also from the storage in caverns and the transportation of hydrogen through former natural gas pipelines. Purity depends on the type of hydrogen (see The colors of a colorless element) introduced into the system, the storage methods implemented in the system, and the type of pipes used (recycled natural gas pipeline or new ones).

When stored in caverns, gas drying is necessary in all cases. Depending on the prior use, residues of natural gas or oil remnants on the cavern walls may cause contamination, requiring their removal in above-ground facilities to achieve the necessary quality.

Contaminants originating from pipelines depend on the age of the pipelines and the gases transported in them previously. Contaminants are particularly high in repurposed natural gas pipelines, especially during the transition period. It is expected that long-chain hydrocarbons, similar to sulfur compounds, will present uncertainties over several years. Impurities from the pipelines can be easily and relatively inexpensively removed through adsorptive gas cleaning. Cleaning of the pipelines at the time of transition might be possible, but practical experience is lacking.

Currently, gas treatment is already carried out before fuel cells or natural gas stations. Various gas treatment processes with a Technology Readiness Level (TRL) of 9 are available. These methods (pressure swing adsorption, selective membrane, palladium diffuser) can produce the quality necessary for heavy-duty vehicles. However, gas treatment incurs additional costs, the magnitude of which depends on the method, the location of the treatment facility, its size, and the type of components to be removed. For example, a local pipeline system supplied with renewable hydrogen (regular PEM) and new pipes does not require any further treatment beyond dehydration for use in HDV. In most cases, the gas drying unit is already integrated into the electrolyzer system. If an additional gas drying unit is required, it could incur costs of 0,147 €/kg in addition to the calculated production cost. In a system with unused pipes and integrated cavern storage, gas purification is more complex. In that case, costs for treatment can range from 0,237 €/kg H_2 to 1,09 €/kg H_2.

During the initial period, it is expected that the H_2-purity of the EHB may not meet the requirements for Fuel Cell Trucks. Furthermore, it is unclear what purity requirements will be set at the European level for injection into the future gas network and requires coordination

[48] NAGas, „DIN EN 17124 Wasserstoff als Kraftstoff - Produktfestlegung und Qualitätssicherung für Wasserstoffbetankungsanlagen zur Abgabe gasförmigen Wasserstoffs - Protonenaustauschmembran (PEM)-Brennstoffzellenanwendungen für Fahrzeuge; Deutsche Fassung EN 17124:2022“.
[49] Lubenau u. a., „Hydrogen quality in an overall German hydrogen network“; EMCEL, „Reinheit von Wasserstoff: Wer nutzt welche Bezeichnung?“

(coordination at the CEN-TS level). However, in the long term, it is expected that this level of purity can be ensured.

Summary

	On-site Production	Trailer delivery	Pipeline
Concept	Producing Hydrogen with an electrolyzer on or near the HRS site	Trailer delivery with compressed or liquefied hydrogen.	Using Pipeline Network to
Recommended storage method	- Large Scale Storage due to fluctuation in renewable production	- Depending on the delivery rate, storage can be smaller	- Small storage for pressurizing and the possibility to refuel multiple cars at once
Site selection criteria	- Water availability - Renewable energies, or strong enough grid access	- None	- Available pipeline access point
Advantages	- Low hydrogen prices - High-Quality hydrogen - Low GHG emissions in transport	- Easy implementation and low investment cost	- Low hydrogen prices - Reliable supply
Disadvantages	- Higher efforts for permits - High investment costs - Large hydrogen storage needed - Balance H2 production and demand. Maybe need additional hydrogen demand (e.g. local industry)	- Supply dependencies - Higher GHG-Emissions - Higher hydrogen cost due to transport costs	- Low availability of pipelines and high investment costs, when building new

5. HRS design and equipment

When developing the design of an HRS, a number of decisions have to be made. For example regarding the technical specifications and requirements for the fuel station. This includes choosing between compressed or liquid hydrogen, determining the number and type of hydrogen dispensers (e.g., 350 bar / 700 bar), ensuring the availability of high-pressure or low-pressure hydrogen, and implementing safety and environmental measures.[50]

The components of an HRS

Refueling stations are configured for optimum performance based on the hydrogen inlet pressure. The hydrogen can be produced on-site most frequently via electrolysis or, what is more common, delivered to the site and fueled directly from a tube trailer or via on-site storage. A typical HRS consists of the following components:

1 Hydrogen storage
   1a in form of a Trailer
   1b for 350 bar technology
   1c for 700 bar technology
2 Dispenser
3 Compressor
4 Cooling unit
5 Control technology

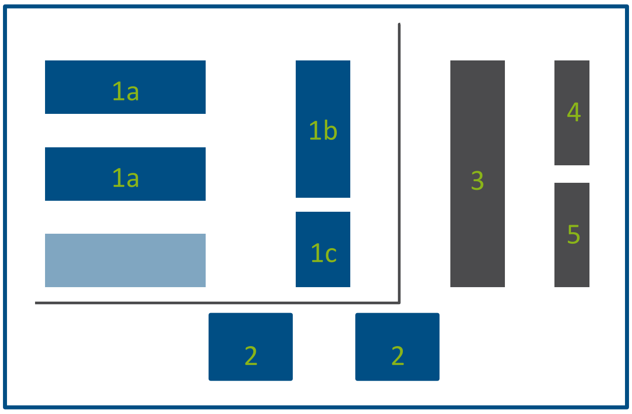

Figure 9: HRS Components Layout

In addition, areas for a fire protection wall, maintenance, and safety measures should be considered. Depending on the chosen technology, some components are not necessary to consider. An HRS without the fuel pump and any sales buildings has a space requirement of approx. 500 – 1500 m². The following text[51] gives a better overview of the components.

[50] Hirschl u. a., „Zwischenbericht zum Gutachten für den Klimaplan Brandenburg - Erarbeitung einer Klimaschutzstrategie für das Land Brandenburg".
[51] Haskel, „Haskel Website".

1. Hydrogen Storage Technologies

There are different types of storage technologies, displayed in the following table.

Table 6: Hydrogen Storage Technologies

Compressed (gas)	Liquefied (liquid)	Cryo-compressed
Energy-intensive method	Even more energy-intensive than compression, higher production cost	
Stored in pressure vessels*	Stored at approx. 20K (-253 C), requires constant cooling	High-pressure and cryogenic storage vessels to increase gravimetric and volumetric capacities
The most commonly used method	Method rarely available	Method is still in development- safety issues not fully explored

*Cooled gas when refueling passenger vehicles

Depending on the location and capacity of the station, hydrogen can be stored in liquid (rarely), medium, or high-pressure gas - the average pressure at the hydrogen station is about 500 bar, and the high pressure is about 900 bar.

For storage, different pressure vessels are needed, which can be found in the following table.

Table 7: Pressure Vessels

HP 900-950 bar, type IV tanks	MP 450- 550 bar, steel types I and II

The compressed gas is stored in the system until required for dispensing at the point of use. The storage is controlled by specially designed valves, fittings, and electrical controls designed to regulate pressure and interact with the dispenser and vehicle as needed.

Tanks are the “pressure banks”. Vehicles are most often refueled by equalizing the pressure after connecting the refueled vehicle successively with low, medium, and high-pressure banks.

2. Dispenser

The dispenser is designed to emulate traditional fueling methods, the hydrogen is dispensed via a nozzle controlled by a smart valve which regulates the flow rate of the gas to fill the vehicle to the required pressure in accordance with the fueling protocol.

Hydrogen refueling stations operate at different pressures, such as 350 bar (35 MPa) or 700 bar (70MPa). H70 stands for refueling 700 bar and H35 stands for refueling with 350 bar. More information can be found in the following table.

Table 8: Pressure Levels of an HRS

350 bar	700 bar
Buses	Passenger cars
Trucks short range (400km)	Light commercial vehicles
Trains	Trucks long range (800km)

3. Compression

It is an instrumented high-pressure hydrogen compression system for pumping hydrogen for refueling a fleet of vehicles. The most expensive component of the station (apart from the electrolyzer) - 30%- 50% of the price.

Hydrogen is compressed to reduce volume and increase pressure. The most commonly used are structures with several compression stages, with one degree providing a pressure increase of up to about six times due to the strength of seals and valve seats. The compressor is primarily used to replenish the pressure in individual banks as they are emptied. Currently, the aim is to minimize the size of stationary tanks at the station.

4. Cooling unit

The hydrogen cooled to subzero temperatures for fast and efficient filling to ensure the hydrogen can be dispensed safely and to comply with filling protocols i.e. J2601.

During the refueling of the vehicle, the hydrogen flowing through the flow resistance lowers its pressure. Due to the specificity of hydrogen and the so-called reverse effect of Joule'-Thomson, the temperature of this gas increases. This reduces the efficiency/rate of refueling, and the high temperature can threaten the hydrogen tanks located on the vehicle, which have plastic sealing coats. Therefore, in the case of refueling passenger vehicles, hydrogen is cooled so as not to exceed the temperature threshold described in the so-called standard refueling protocol.

Cooling is usually not used for refueling buses and medium-range trucks. This is not economically justified. In these vehicles, larger tanks are used, refueling takes longer, and the pressure reaches 350 bar. Bus and truck manufacturers limit flow rates and secure vehicle tanks through individual refueling protocols that station suppliers must adapt to.

A cooler may also be needed if the hydrogen tanks are located at a great distance from the hydrogen distributors, resulting in an increase in gas temperature due to a loss of pressure over the length of the pipeline. The limit value to which there is no need to build cooling is considered to be about 50 m.

5. Control technology

The control technology is a safety feature to vent any escaped hydrogen safely. Hydrogen is lighter than air so dissipates quickly and safely, should an incident occur.

6. Other components

Heat exchanger - The compressed hydrogen is then passed through a heat exchanger to remove the excess heat from the gas that was generated during the compression process. Specially designed hydrogen-resistant valves and fittings are used to control the highly pressurized hydrogen. These components utilize specific materials that are resistant to hydrogen embrittlement to prevent any cracking.

Hydraulic power unit and controls - The process is powered, monitored, and controlled via the electronic control panel in the non-hazardous zone.

The different types of HRS - The different types of HRS concern the size, vehicle types, and demand. The various characteristics can be found in the following table.

Table 9: Types of HRS[52]

Size	S	M	L	XL
Max. hydrogen throughput per day	200 kg	500 kg	1000 kg	4 000 kg
Vehicle	Passenger Vehicle, Light Duty Vehicle	(Passenger Vehicle, Light Duty Vehicle, buses), Medium Duty Vehicle	(Passenger Vehicle, Light Duty Vehicle, buses), Medium Duty Vehicle, Heavy Duty Vehicle	(Passenger Vehicle, Light Duty Vehicle, buses), Medium Duty Vehicle, Heavy Duty Vehicle
Average hydrogen throughput per day	150 kg	350 kg	700 kg	2 500 kg
Annual demand	1-10t	100 t+	500 t+	900 t+
Refueling nozzle	1	2	2-3	2-4
Size components area	80-250 m2	200-350m2	250-800 m2	Depending on HRS technology

[52] H2Mobility, „Overview Hydrogen Refuelling For Heavy Duty Vehicles“.

P. Rose and F. Neumann estimated the cost of components for hydrogen refueling stations depending on the size for the year 2050:

Table 10: Costs of HRS components for 2050 based on P. Rose and F. Neumann, 2020

Parameter	Unit	S	M	L	XL
High pressure storage	Mio. €	0,26	0,51	1,03	2,06
Dispenser	Mio. €	0,11	0,21	0,43	0,86
Compressors	Mio. €	2,76	5,52	10,65	21,30
Cooling unit	Mio. €	0,12	0,12	0,12	0,12
Safety Features	Mio. €	0,14	0,28	0,56	1,12

Relevant technical standards for HRS

See "A catalog of technical standards and norms for hydrogen refueling stations dedicated for heavy-duty transportation in the BSR"

6. Economic consideration

The chapter deals with the assessment of the economic viability of the HRS. This involves evaluating investment costs, ongoing operational expenses, potential revenue streams, and exploring various business models. Additionally, financial incentives and tax benefits that may apply are investigated.

Cost of Hydrogen

The price of hydrogen is made up of various individual costs.

Filling station costs: These costs relate to the construction, operation and maintenance of the filling station itself.

Compression-, Transport-, and Distribution costs: These costs include the entire procurement and storage process for hydrogen. The chosen distribution method and the distance from the HRS to the production site have a major influence on these costs.

Production costs: Production accounts for the majority of the price of hydrogen. The different production methods and the color of the hydrogen play a major role in this cost item.

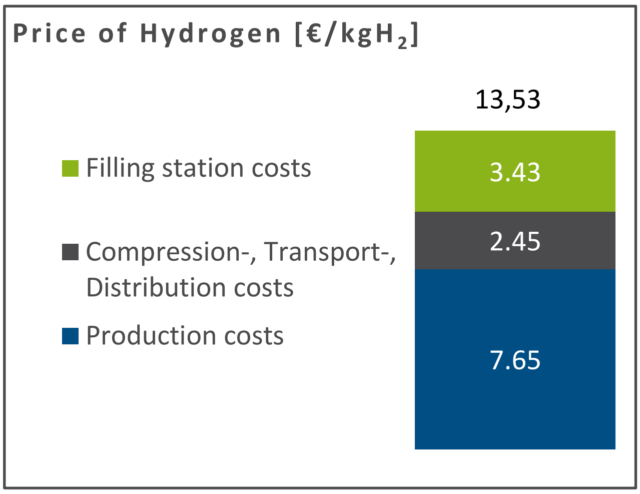

Figure 10: Example of Price Components of Renewable Hydrogen in Germany

Figure 10 shows an example from Germany from 2023. Depending e.g. on the electricity mix and the total amount of HRSs in a country the price is changing. It is generally assumed that the price will fall. This is important to meet the break-even price for Hydrogen compared to Diesel. This break-even price for example in 2030 in Poland is 3,5 €/kg whereas in Germany it is 4,1 €/kg[53].

Economic Considerations on Refueling Station Models

The hydrogen supply of the filling station influences profitability. Looking at the various options for supplying hydrogen filling stations, the following findings can be derived:

- **On-site production with its electrolysis plant**

  If hydrogen is produced directly near the filling station, there are no transport costs. Due to economies of scale, it can be assumed that smaller decentralized plants cost more than large centralized production plants. In addition, with this type of supply, the investment costs are significantly higher and the planning effort is greater.

[53] Basma, Zhou, und Rodríguez, „FUEL-CELL HYDROGEN LONG-HAUL TRUCKS IN EUROPE: A TOTAL COST OF OWNERSHIP ANALYSIS“.

- **Trailer Delivery**

  Delivery with trailers increases hydrogen costs. However, the supply can be controlled according to demand. Trailer delivery is the most common way of delivery but also very pricy compared to pipeline delivery.

- **Pipeline**

  The supply with the help of a pipeline promises flexibility and cheap hydrogen. In the long term, imports from countries with favorable production conditions for hydrogen are to be fed into the pipeline. At present, however, it is not yet clear what connection fees will be charged for pipeline supply. The European Hydrogen Backbone is currently being planned. However, when the first systems can be connected varies from region to region. In the short term, this type of supply is therefore out of the question.

Economic models

The economic dimension of developing HRSs in the HyTruck project is primarily concerned with assessing the costs of producing and delivering hydrogen for trucks and looking at the long-term contribution of hydrogen in meeting the demand for road freight transport energy.

We explore the economic dimension of developing HRSs in three pillars, through a techno-economic analysis (TEA) model of hydrogen supply, a business optimizing model, and an energy systems model. The details of the structure, general inputs, and outputs of each model will be presented. While each model covers one aspect of the economic dimension, they complement each other to provide a general yet insightful picture of the costs of supplying hydrogen for road freight transport.

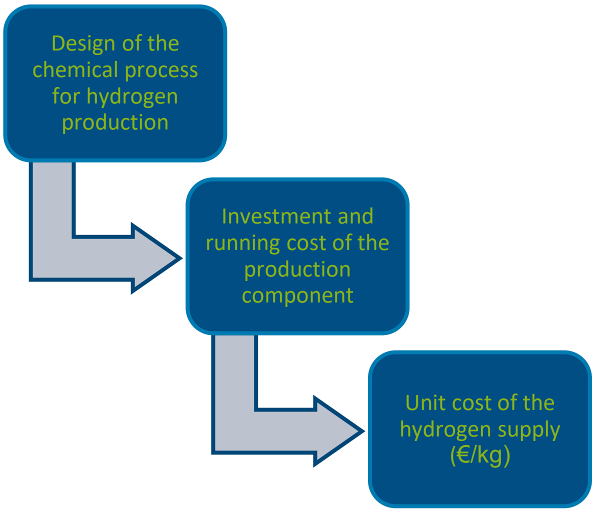

Figure 11: Developing the Model for TEA

Understanding the cost structure associated with producing and delivering hydrogen has an outstanding level of importance for the local authorities that plan to expand HRSs in their region. There are many technical options for hydrogen supply and delivery in place today. However, each technological scenario has its pros and cons that need to be considered carefully by local authorities for developing HRSs. Some of the technical scenarios can result in a high hydrogen cost, affecting the region's desired expansion rate of HRSs.

Detailed economic analysis is executed by the project partner Research Institutes of Sweden (RISE).

7. Greenhouse Gas Emissions

When looking at the environmental impact of a truck and its journeys, there are different scopes of analysis. As shown in Figure 12 it depends on the parts of a life cycle of a truck. If you consider the whole life including production and end of life, the analysis is called life cycle assessment. For this analysis, you can find an example in the next chapter. Some information on the environmental impact only includes e.g. the emissions while driving. Then it is called a Tank-to-Wheel-Analysis.

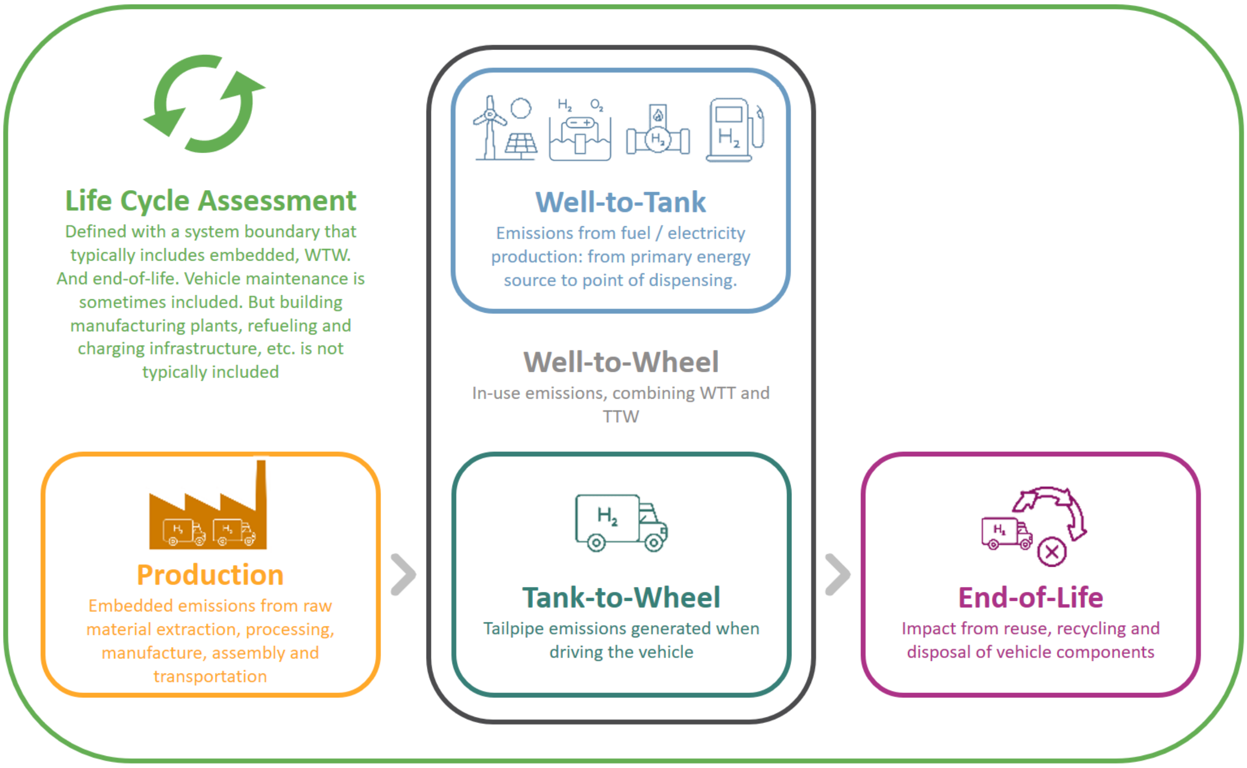

Figure 12: Impact Assessment Methods for Trucks

LCA considerations on Refueling Station Models

The hydrogen supply of the filling station influences profitability. Looking at the various options for supplying hydrogen filling stations, the following findings can be derived:

- **On-site production with its electrolysis plant**

  On-site production reduces emissions in transport. The efficiency of smaller production plants is usually less. Nevertheless, the efficiency of not relying on transport usually makes up for this.

- **Trailer Delivery**

  The supply using trailers causes additional emissions.

- **Pipeline**

  The construction and operation of pipelines consume resources and energy. It should also be taken into account that the overall efficiency can be significantly lower with imported hydrogen. When hydrogen is liquefied for transport, additional energy is required. The longer the transport and the more changes in the aggregate state or pressure level take place, the lower the efficiency and the higher the energy expenditure.

Life Cycle Assessment: a study on H_2-based long-haul road transportation

During the HyTruck project, a detailed LCA has been conducted by the Project Partner University of Chalmers. As there are several pathways for the production, transmission, and distribution of H_2, the characteristics of a future supply chain for H_2 for use in trucks are still not defined. Therefore, our analysis will evaluate several pathways of centralized and distributed production of H_2 as well as several pathways for distribution and several vehicle configurations. We expect the results of the analysis to be used to inform decision-makers on the actual environmental impacts of deploying hydrogen for long-haul trucks along different pathways. In the same way, we expect to point out the environmental burden hotspots in the supply chain.

The study focuses on long-haul road transportation based on H_2 in Sweden. It demonstrates that substituting the current fleet of internal combustion engines with H_2-powered vehicles may in fact not reduce GHG emissions, as the production of H_2 can be extremely carbon-intensive unless renewable energy is used for producing H_2. As GHG emissions mitigation is one of the main drivers for transport decarbonization, it is fundamental to guarantee that the technology substitution will not come at the expense of shifting those GHG emissions upstream in the energy production supply chain. Thus, the goal of this analysis is to estimate the environmental impacts of using H_2 in trucks in Sweden via life cycle assessment (LCA). This analysis will be carried out over the entire supply chain, including H_2 production, transmission, distribution, and use in FCEV trucks and ICEVs powered by H_2. Truck manufacturing is also included in the study.

8. Site Selection

This chapter is about the questions of where to build up HRSs and the goal of finding a location.

The BSR, TEN-T, and pilot projects

The HyTruck project is set in the BSR, an area covering 2.9 million km^2, and home to around 80 million inhabitants. Stretching from Eastern Germany to Northern Finland, it involves 9 states (Germany, Poland, Lithuania, Latvia, Estonia, Finland, Denmark, Sweden, and Norway). Along a large number of these states runs the Trans-European Transport Network (TEN-T). It contains the main traffic axes for heavy-duty -traffic in Europe.

HyTruck features five selected pilot regions along the TEN-T in the BSR with the goal to set up HRSs.

Figure 13 shows the TEN-T as well as the pilot regions.

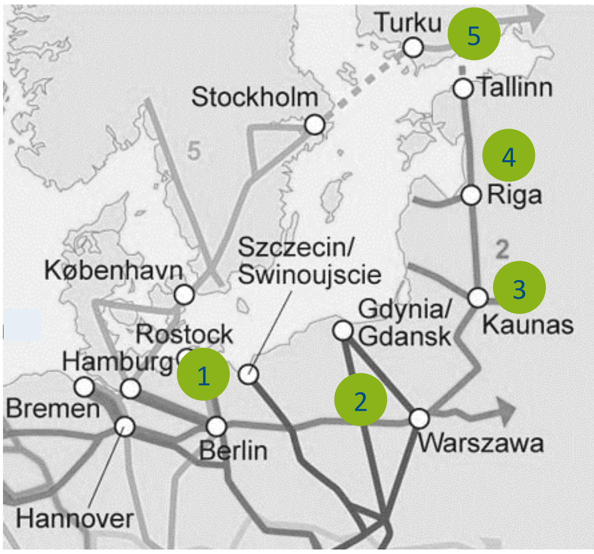

Figure 13: Map of BSR, TEN-T and the Pilot Regions

Rostock Region (Germany) → There are currently 2 HRSs in the region of Rostock and several more in the region of Berlin.

Poznań region (Poland) → Currently 1 HRS with 350/ 700 bar with blue hydrogen.

Kaunas region (Lithuania) → No HRS currently but published tenders for 3 HRSs with renewable hydrogen.

Vizdeme Planning Region (Latvia) → No HRS currently but several companies plan to invest in the technology.

Helsinki (Finland) → No HRS currently but there are positive government funding decisions for tendering applications for the use of Power2X (P2X) with 350/ 700 bar and renewable hydrogen.

Relevant parameters for location selection

Public authorities should consider various parameters when selecting a location to build an HRS. Notably, an estimation of how much surface area is needed to build, as well as the amount of undeveloped land in the territory are pivotal factors. The following parameters should also be thoroughly surveyed:

Geographical position: Check the surrounding area for example for infrastructure (e.g. roads, energy supply), residents, and cities. Also, have a look at the property and soil conditions, etc.

Accessibility for vehicles and potential customers: Since all of the customers will be using vehicles, accessibility needs to be given. Also, for heavy-duty traffic, the location has to be accessible.

Availability of hydrogen suppliers: When searching for a location, it is advisable to look for nearby hydrogen suppliers. Renewable energy plants or the potential to build them are also helpful. Storage should also be considered and space for this application should be factored in.

Compliance with regulatory requirements: In the European context the Alternative Fuels Infrastructure Regulation (AFIR) has to be considered. You can find more information in Chapter 9: Permits and Regulations. There you can also find information on other regulatory requirements.

Network compatibility: In the context of a network, such as the TEN-T it is important to look out for HRSs in neighboring countries. Especially in bordering regions, it is not necessary to build up more HRSs than needed in a short distance. Currently, there is no recommended HRS network for the whole TEN-T network.

The HRS site selection tool

The "Spatial Planning Toolkit" is an innovative tool designed to support the site selection process for hydrogen refueling stations within the Nordic and Baltic region's TEN-T corridors. By leveraging established geographic analysis methods such as suitability analysis, the Analytic Hierarchy Process (AHP), and spatial optimization, this toolkit synthesizes multiple layers of geographic data to identify locations for infrastructure development. It is tailored to support the growing hydrogen economy, addressing the intricate balance between environmental sustainability, economic viability, and logistical efficiency.[54]

Engage Stakeholders Across the Entire Hydrogen Value Chain:

- **Collaborative decision-making**: the tool facilitates a participatory approach allowing stakeholders involved in production and distribution, as well as end-users, to contribute to and influence site selection criteria, ensuring a balanced representation of interests.
- **Transparency in Planning**: Promotes an open and transparent process, providing stakeholders with clear insights into the decision-making framework, enhancing trust, and fostering consensus.
- **Real-Time Scenario Analysis**: Enables dynamic adjustment of planning parameters to reflect stakeholders' feedback, allowing for the simulation of various development scenarios and their outcomes.

[54] Greene, Ogden, und Lin, „Challenges in the designing, planning and deployment of hydrogen refueling infrastructure for fuel cell electric vehicles“.

How Users Can Explore Detailed Information About Hydrogen:

- **Interactive Geographic Layers**: Users can delve into a range of GIS layers, such as existing infrastructure and environmental constraints, to gain a comprehensive understanding of the hydrogen landscape.[55,56]
- **Discover stations service area**: the toolkit enables users to analyze the service area of possible refueling stations within a 100 km road distance.
- **Data-Driven Insights**: The toolkit aims to facilitate access to databases on hydrogen demand, potential supply regions, and logistical considerations, empowering users with actionable insights.
- **Customizable scenarios**: Offers the ability to create tailored scenarios summarizing key data points and analytics, aiding stakeholders in strategic planning and communicating regional specifics with external parties.[57]

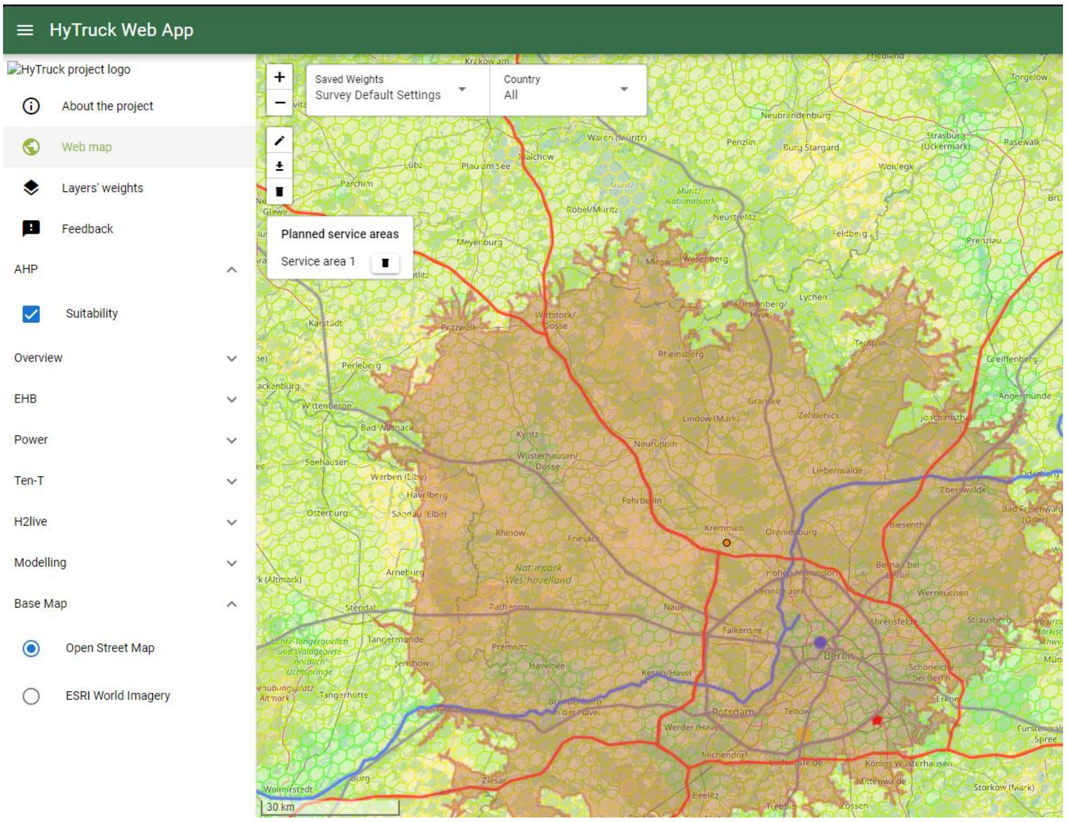

Figure 14: Spatial Planning Toolkit - Mockup

[55] Karipoğlu, Genç, and Akarsu, „GIS-based optimal site selection for the solar-powered hydrogen fuel charge stations".
[56] Messaoudi et al., „Site selection methodology for the wind-powered hydrogen refueling station based on AHP-GIS in Adrar, Algeria".
[57] Shi, Li, and Xu, „Two-stage site selection of hydrogen refueling stations coupled with gas stations considering cooperative effects based on the CRITIC-ITFAHP-MABAC method: A case study in Beijing".

Where to find the tool?

A manual for the tool can be found here: https://hytruck.landscape-geoinformatics.eu/docs/
The tool can be found here: https://hytruck.landscape-geoinformatics.eu/map

Further tools for renewable hydrogen

New European Wind Atlas[58]

This Online-Dashboard shows you the potential for wind energy in Europe. This is useful for renewable hydrogen, as wind energy is renewable and a potential energy source for the production. Along the shores of the Baltic Sea there is a high wind energy potential, which should be taken into account when building up HRSs in the BSR. Looking out for renewable production potential while searching for a suitable site can reduce production costs and GHG emissions.

The tool can be found here: https://map.neweuropeanwindatlas.eu/

Hydrogen Marketplace

The Localiser Hydrogen Marketplace (Figure 15) is a digital platform, designed to link various stakeholders in the hydrogen sector. It connects land suppliers, producers, pipeline operators, government representatives, consultants, and end-users. Marketplace provides a space for identifying potential partnerships, where users can map hydrogen supply and demand in their region, search for project partners, as well as write and receive messages directly through the platform.

Hydrogen Marketplace aims to engage stakeholders across the entire hydrogen value chain:

- **Businesses and organizations** can coordinate their hydrogen offerings and demands,
- **Regional authorities and planners** can gain insights into the region's hydrogen industry development,
- **The energy industry** can stay updated on the status and planning of hydrogen infrastructure.

After gaining access to the marketplace, users can explore detailed information about hydrogen:

- **Hydrogen production details:** pressure, status, purity, and quantity for electrolyzers, photovoltaic (PV) and wind farms,
- **Planned infrastructure:** planned hydrogen hubs, refueling stations, pipelines, and Ten-T Roads

[58] NEWA, „New European Wind Atlas“.

- **Usage:** cogeneration plants, storage options, district heating opportunities, vehicle conversion.

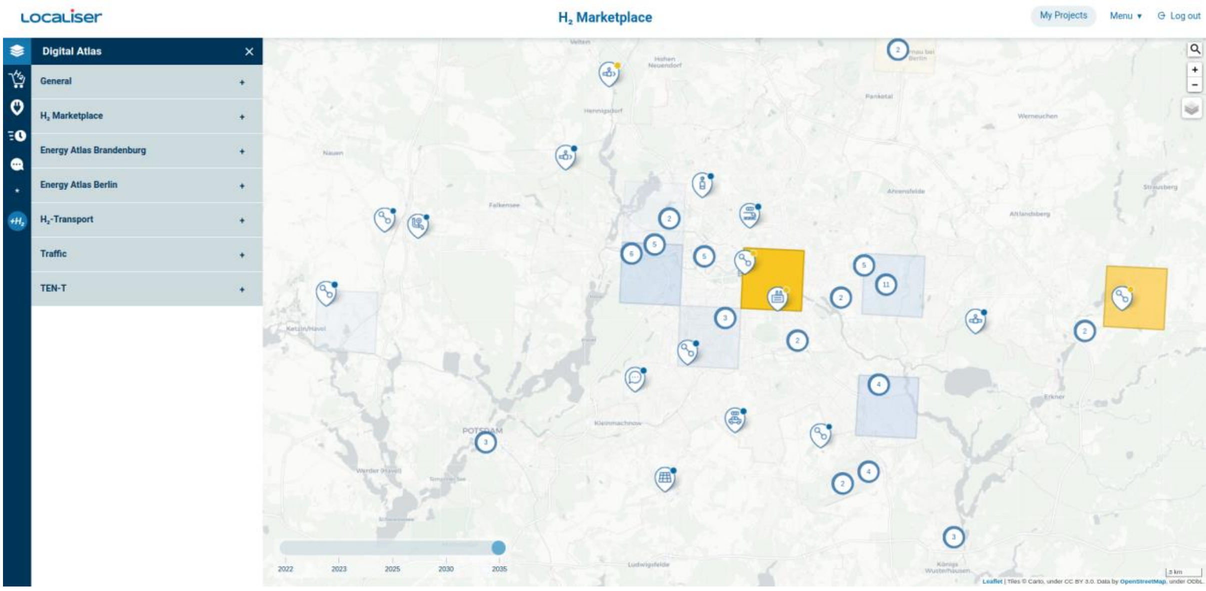

Figure 15: Hydrogen Market Place

There are a lot more tools, which can be useful in the decision-making process. It is advisable to keep an eye out for these in your region.

9. Permits and regulations

The EU has deemed hydrogen "*essential to support the EU's commitment to reach carbon neutrality by 2050*"[59]. In order to organize and anticipate a growing hydrogen sector in the next years, the Union has therefore issued a considerable amount of legislation regarding the large-scale development of what is yet still a rather rare use of the technology.

It is noteworthy that the following legislation was passed as, respectively, a European Regulation (passed by EU institutions, and directly applicable to member states) and a European Directive (as a guideline with targets and objectives, but not directly applicable: the member states must pass laws internally that comply with the goals set in the Directive). The choice of these two formats demonstrates a strong European determination to make progress on its hydrogen policy, in cooperation with the member states, to ensure a satisfying level of integration and interoperability from one country to another.

In that regard, the following legislation must be closely followed by the pilot regions, to correctly implement the corresponding European hydrogen long-term strategy. In addition to the rules addressed in this chapter, public authorities should also thoroughly research additional national or local laws relevant to the building of energy infrastructure in general, and hydrogen infrastructure in particular. Building permits, as well as safety and environmental regulations, should notably be closely abided by. The following European requirements remain, in any case, legally binding and cannot be departed from in the context of the HyTruck project.

Regulation for the deployment of AFIR[60]

The European Commission's AFIR outlines key provisions for the development and accessibility of HRSs within the TEN-T network and urban nodes as defined and listed in Regulation (EU) No 1315/2013. The requirements are the following:

Publicly accessible HRS: HRSs constructed under the AFIR are intended for public use and should be accessible by the general public like conventional refueling stations.

Density on TEN-T network: The directive mandates a minimum of one HRS for every 200 kilometers in both directions on the TEN-T network, promoting hydrogen infrastructure development.

Cross-border coordination: Member States are required to coordinate to ensure that the maximum 200 km interval between two HRSs on the TEN-T network is not exceeded, particularly on cross-border road sections.

Urban node integration: Within urban nodes, at least one HRS should be established. It's encouraged that HRSs within urban nodes be located in multimodal hubs such as ports and train depots for interoperability and accessibility to the public.

---

[59] European Commission, „A Hydrogen Strategy for a Climate-Neutral Europe".
[60] European Parliament, European Council, „REGULATION (EU) 2023/1804 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 13 September 2023 on the Deployment of Alternative Fuels Infrastructure".

Capacity: Each HRS should provide a minimum of 1 ton of gaseous hydrogen per day at 700 bar.

Payment accessibility: Users of FCEVs should be able to pay easily at HRSs using widely accepted payment methods without requiring a subscription, ensuring public accessibility to the refueling infrastructure.

Consumer information: HRS operators must provide comprehensive information, notably by electronic means, including station availability, waiting times, and pricing at different stations.

Location on TEN-T road network: HRSs deployed along the TEN-T road network should either be directly on the network or within a 10 km driving distance from the nearest TEN-T road exit.

Accessibility and non-discrimination: HRSs must be accessible to all individuals, irrespective of their physical traits or disabilities, in accordance with Directive (EU) 2019/882. The aim is to promote inclusivity.

Compatibility with vehicle types: HRS infrastructure should be designed to accommodate both heavy-duty and light-duty vehicles, offering at least gaseous hydrogen at 700 bar. It should also anticipate the probable rise of technologies like liquid hydrogen for heavy-duty vehicles, and dispensers operating at 350 bar for lighter-duty vehicles.

Clean Vehicles Directive[61]

The Directive (EU) 2019/1161 of June 20th, 2019, commonly referred to as the “Clean Vehicles Directive” (CVD), sets out statutory minimal shares of “clean vehicles” or “zero-emission heavy-duty vehicles” among those newly acquired by means of public procurement, for each individual member state. All entities subject to an obligation of acquiring vehicles by means of public procurement are concerned, but only the aggregate share of vehicles in total counts in assessing if countries meet the target or not.

This guideline specifically targets the procurement of N2 and N3 vehicles —trucks and lorries— under Article 4(1) of EU Regulation 2018/858. Lighter cars or buses typically do not fall within these categories.

The CVD amends Directive 2009/33/EC on the promotion of clean and energy-efficient road transport. It covers two distinct periods, from August 2nd, 2021, until the 31st of December 2025, and from January 1st, 2026, until the 31st of December of 2030. The second period heightens the ambitions for the minimum share of clean and zero-emissions vehicles in states' procurements, as outlined per country.

Each country had an obligation to transpose the Directive into their national law by August 2nd of 2021. This obligation has been respected, and the rules set out in the Directive are now applicable in every member state of the EU. An index of each relevant piece of national legislation for HyTruck pilot region states is provided in the table at the end of this section.

[61] European Council, European Parliament, „Clean Vehicles Directive“.

Furthermore, by definition of the CVD and related instruments[62,63] , a “clean heavy-duty vehicle” is a vehicle of category N2 or N3, which uses one of the following alternative fuels instead of fossil fuels: electricity, hydrogen, biofuels, synthetic and paraffinic fuels, natural gas (including biomethane), as compressed natural gas or liquefied natural gas or liquefied petroleum gas. The same sources provide that synthetic and paraffinic fuels, natural gas, and LPG do not qualify if they are mixed with conventional fossil fuels.

We were able to recover information on the relevant transposition legislation for all states involved in the HyTruck pilot projects, except Lithuania. It appears, however, that Lithuania has passed a law in this sense, following the Directive´s requirements exactly, for both time periods. Lithuania, like all other concerned Member States, has decided to implement the same minimal targets as those set in the Directive. No concerned Member State has decided to raise these minimal thresholds, as was their sovereign competence in regard to the partially binding nature of a European Directive.

The pilot region states must include the following minimum percentages of “clean heavy-duty vehicles”:

Table 11: Country-specific Targets for clean heavy-duty Vehicles

Country	Minimal share until 31/12/2025	Minimal share between 01/01/2026 and 31/12/2030
Germany[64]	10%	15%
Latvia[65]	8%	9%
Poland[66]	7%	9%
Finland[67]	9%	15%
Lithuania	8%	9%

[62] European Council, European Parliament, „DIRECTIVE 2014/94/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 22 October 2014 on the Deployment of Alternative Fuels Infrastructure“.
[63] European Council, European Parliament, „Renewable Energy Directive II“.
[64] Deutscher Bundestag, „Gesetz zur Umsetzung der Richtlinie (EU) 2019/1161 vom 20. Juni 2019 zur Änderung der Richtlinie 2009/33/EG über die Förderung sauberer und energieeffizienter Straßenfahrzeuge sowie zur Änderung vergaberechtlicher Vorschriften“.
[65] Latvian parliament, „Grozījumi Publisko iepirkumu likumā Izdarīt Publisko iepirkumu likumā (Latvijas Vēstnesis, 2016, 254. nr.; 2018, 89., 196. nr.; 2019, 41., 45., 253. nr.; 2020, 84.C nr.) šādus grozījumus“.
[66] Polish parliament, „USTAWA o zmianie ustawy o elektromobilności i paliwach alternatywnych oraz niektórych innych ustaw“.
[67] Finnish parliament, „Laki ajoneuvo- ja liikennepalveluhankintojen ympäristö- ja energiatehokkuusvaatimuksista“.

Country-specific policies and their influence

The pilot states have taken steps towards accompanying the development of national hydrogen economies. As the EU has set multiple binding targets for the share of renewable energy in final energy consumption, a financial participation of states in the build-up of renewable hydrogen infrastructure was needed to support investors with the high costs associated with the industry. However, when such funding schemes exist in the HyTruck pilot states, they often appear limited and insufficient compared to the scale of the climate ambitions of the EU, as was until recently laid down in the so-called Renewable Energy Directive II[68], and raised with the recent adoption of the Renewable Energy Directive III[69]. Nonetheless, a set of country-specific funding plans was usually made available at the state level for investors to apply for and receive state sponsorship for the development of hydrogen infrastructure. As mentioned above, the targets for the use of renewable hydrogen have very recently been raised by the European Union. It is therefore expected that the national laws and funding options in the pilot states will experience significant changes before mid-2025, which is the timeframe states have to transpose the Directive into their national jurisdictions. The information contained in this chapter is thus certainly to become soon outdated, but this should still give a relatively clear overview of the current situation regarding national funding schemes in the HyTruck pilot states.

So far, among the five pilot states, Germany and Poland seem to have taken the lead for funding options of renewable hydrogen infrastructure.

In **Germany**, the National Innovation Programme for Hydrogen and Fuel Cell Technology (2016-2026), also referred to as NIP 2, is the main funding instrument for any renewable hydrogen-related project aimed at developing the H2 infrastructure in the country. On the side of taxation and fiscal incentives, it is notable that since January 1st of 2021, renewable H_2 is exempt from the levy under the "Renewable Energies Act", adding to the attractiveness of the sector for new investors.

Poland has had an ambitious hydrogen strategy since 2021, with perspectives until 2030. On the practical side, most observers agree that the legislative framework that is meant to help investors realize the so-called "H_2-valleys" in the imparted time is far from sufficient, and little seems to have been done by the state of Poland to incentivize investors into producing renewable H_2 in the country. It is thus forecast that most of the hydrogen needs of Poland in both the industry and transport sectors will have to be met through the importation of grey hydrogen from outside the EU. However, the Ministry of Climate and Environment has set up the National Fund for Environmental Protection and Water Management, which is currently working on investing 100M PLN (about 23M euros) into the building of 20 hydrogen refueling stations. The first round of applications to receive grants from the Fund ended in early 2023, but the recently raised ambitions regarding hydrogen, expected through the perspective of

[68] European Council, European Parliament, „Renewable Energy Directive II".
[69] European Parliament, European Council, „Renewable Energy Directive III".

the RED 3, allow for anticipating that similar or more comprehensive endeavors will be initiated by Poland in the upcoming months.

Finland currently only allows for partial funding of investments in national hydrogen-related projects, with no major subsidies for renewable H_2 production specifically. There again, the lack of clear incentives and state sponsorship of the development of the sector is expected to be addressed while Finland transposes the targets contained in the RED 3 into their national laws, as local demand for hydrogen is already relatively high due to the heavy industries traditionally operating in the country.

In **Lithuania**, we observe a similar lack of a comprehensive legislative framework aimed at supporting the development of renewable H_2 production, transport or distribution at the scale of the state. However, the Ministry of Energy has approved the funding of the first three renewable H_2 projects in relation to the transport sector, in January of 2023. A total of 13M euros will be allocated for building a total electrolysis capacity of 2.5 MW from renewable sources in three cities, aimed at providing the hydrogen necessary to a fleet of local buses. While no comprehensive funding plan has been made public as of November 2023, it is likely that the interest expressed by the government in renewable H_2 for mobility, coupled with the higher minimal targets from the RED 3, will spur change in Lithuania in the medium-term as well.

Latvia seems to be the only pilot state without any major funding scheme nor individual granting measure at the scale of the state. Renewable hydrogen projects have been initiated in Latvia, but so far they have only been funded by external funds, notably Swedish funds or the Interreg Baltic Sea Project. There again, it can reasonably be expected that the RED 3 targets can help incentivize the Latvian government to develop a national investment scheme to support the development of renewable H_2 in the country.

10. Networking and Collaborations

To build a successful and sustainable HRS it is important to engage and collaborate with different stakeholders. It is necessary to determine whether partnerships and collaborations are essential or beneficial. On the one hand, this refers to the fact that a single HRS can be operated successfully. On the other hand, cooperation between the public authorities of the neighboring countries in a region plays an important role. With a joint development plan, it is possible to set up an entire HRS network sustainably and profitably.

Potential partners and how to collaborate

Partners for the HRSs build-up could be: e.g. property manager/ owner, construction office, factory inspectorate, fire protection assessor/firefighter, architect, measurer, structural engineer, approved monitoring agency

Partners for the operation of the HRS could be: e.g. hydrogen suppliers, vehicle manufacturers, local companies or government agencies, also from neighboring countries to plan the HRS network together

Partners for a whole hydrogen system could be:[70] The production and usage of hydrogen should be seen as a whole system. Therefore, it is recommended to connect with other companies or stakeholders of different types of usages for hydrogen. This could be using hydrogen for electricity or heating, as synthetic fuel, or as raw materials in the industry. Gain an overview of your region and the nearby companies.

- Research & Development *(project developers, consultants, associations, institutional investors)*
- Technology providers *(storage operators, vehicle manufacturers & Original Equipment Manufacturers, refilling station operators, electrolyzer operators)*
- Energy and heating system sector *(electricity utilities, Renewable Energy System plant operator, petroleum industry, gas Transmission System Operator, industrial gas companies, heating system manufacturers)*
- Public companies *(municipal utilities, politics, Non-Governmental Organizations)*
- Transport sector *(heavy-duty transport, seaports, buses, rail transport, other commercial vehicles, aviation)*
- Industrial sector *(steel industry, cement industry, chemical industry, gas industry, ICT industry, building sector)*

Partners to reference the HRS online could be: Several easily accessible websites are available, that provide a register of operating HRSs in Europe and beyond. Having your HRS referenced in such customer-oriented products is crucial in the context of the HyTruck project since the overall goal is to promote the development of hydrogen in the transport sector by convincing consumers that the technology is reliable, for short- and long-haul drives.

[70] Schlund, Schulte, und Sprenger, „The Who’s Who of a Hydrogen Market Ramp-Up“.

Referencing your HRS will not only be a useful advertisement tool, but it will also contribute to the broader decarbonization effort of the transport sector. To do so, please actively get in contact with:

- H2.live
- H2stations.org
- Localiser.de
- h2-stations.eu

Stakeholder management: After identifying stakeholders, you have to analyze them to find out if they are important and useful for your purpose. You can analyze them through references, other projects, or their network. For a successful collaboration, make sure to distribute tasks, identify milestones, and monitor the process. Keep this already in mind when engaging them. To engage stakeholders tendering is a useful method.

How to tender for the construction of hydrogen refueling stations

Tendering for the construction of a hydrogen refueling station offers a multitude of advantages that extend beyond the mere establishment of the infrastructure. The process of tendering, which involves competitive bidding by contractors to secure the project, not only heightens the chances of optimal value-for-money and streamlined construction but also fosters innovation and accountability through competition, exigent client expectations, and research and development processes. Throughout the tendering process, public authorities promote the development of cutting-edge technology, create economic opportunities, and ensure the best use possible of public funds to realize general interest-oriented projects.

Tenders can be designed in a variety of ways. More than the layout or form it takes, what matters most is the content. It should be clear, straightforward, and completely encompass the client's expectations. For the sake of clarity, most procurement documents take the following structure:

Client: Identity of the public authority: name, address, person of contact, phone number, website…

Subject matter: Description of the overall project, and individual lots (e.g. sub-projects, when applicable)

For an HRS, this includes e.g. a summary description of the infrastructure, the hydrogen pressure, the expected volume of H_2 delivery, the number of nozzles, H_2 storage methods, and whether the HRS should include parking areas for large trucks, HRS operating hours; potential maintenance/personnel contracts. Anything relevant to the expectations of the client and the subject matter of the project should be contained in this section. Where the general project is subdivided into lots, each lot should be identifiable in this section and be as precisely defined as possible.

Procedure: A list of administrative details, necessary to complete the procedure: language spoken with the client, deadline for submitting the application.

Contract award: A short description of the financial details of the contract.

The client may determine the price of the project/lots in advance and disclose it in this section. The criteria for determining the contract awardee may also be disclosed in this section, along with their respective weight in the decision-making process.

Additional information: Any other piece of information relevant to the candidates: e.g. address of court competent for lodging an appeals or conciliation procedure.

List of sources

Adolf, Jörg, Christoph H. Balzer, Jurgen Louis, Uwe Schabla, Manfred Fischedick, Karin Arnold, Andreas Pastowski, und Dietmar Schüwer. „Energy of the Future? : Sustainable Mobility through Fuel Cells and H2 ; Shell Hydrogen Study“. Hamburg: Shell Deutschland Oil, 2017. http://nbn-resolving.de/urn:nbn:de:bsz:wup4-opus-67865.

Basma, Hussein, Yuanrong Zhou, und Felipe Rodríguez. „FUEL-CELL HYDROGEN LONG-HAUL TRUCKS IN EUROPE: A TOTAL COST OF OWNERSHIP ANALYSIS“, o. J.

Bundesministerium für Wirtschaft und Klimaschutz BMWK. „Pressemitteilung - Bundeskabinett beschließt Gesetzentwurf zur Schaffung eines Wasserstoff-Kernnetzes“, 24. Mai 2023. https://www.bmwk.de/Redaktion/DE/Pressemitteilungen/2023/05/20230524-bundeskabinett-beschliesst-gesetzentwurf-zur-schaffung-eines-wasserstoff-kernnetzes.html.

Daimler truck. „Entwicklungsmeilenstein erreicht: Daimler Truck testet Brennstoffzellen-Lkw mit Flüssigwasserstoff“, 27. Juni 2022. https://media.daimlertruck.com/marsMediaSite/de/instance/ko/Entwicklungsmeilenstein-erreicht-Daimler-Truck-testet-Brennstoffzellen-Lkw-mit-Fluessigwasserstoff.xhtml?oid=51975637.

dena, Deutsche Energie-Agentur, Hrsg. „STUDIE: Geschäftsmodelle für dezentrale Wasserstoffkonzepte – Zeit zum Nachsteuern“, Mai 2023. https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2023/STUDIE_Geschaeftsmodelle_fuer_dezentrale_Wasserstoffkonzepte_-_Zeit_zum_Nachsteuern.pdf.

Deutsches Bundestag. „Gesetz zur Umsetzung der Richtlinie (EU) 2019/1161 vom 20. Juni 2019 zur Änderung der Richtlinie 2009/33/EG über die Förderung sauberer und energieeffizienter Straßenfahrzeuge sowie zur Änderung vergaberechtlicher Vorschriften“, 20. Juni 2021. https://bmdv.bund.de/SharedDocs/DE/Anlage/G/gesetzesentwurf-foerderung-sauberer-energieeffizienter-strassenfahrzeuge.pdf?__blob=publicationFile.

Ehret, Dr Oliver. „Wasserstoffmobilität: Stand, Trends, Perspektiven“. Herausgegeben von DVGW Deutscher Verein des Gas- und Wasserfaches e. V., Januar 2020. https://www.dvgw.de/medien/dvgw/forschung/berichte/g201910-abschlussbericht-h2-mobilitaet.pdf.

EMCEL. „Reinheit von Wasserstoff: Wer nutzt welche Bezeichnung?“, 16. Dezember 2020. https://emcel.com/de/reinheit-von-wasserstoff/.

Enginius. „FACTSHEET – ENGINIUS“, 28. Juni 2022. https://www.enginius.de/wp-content/uploads/2022/06/ENGINIUS_Factsheet_final_D.pdf.

Esoro. „Weltweit erster Wasserstoff-LKW mit Anhänger, der die LKW-Anforderungen für die Coop-Logistik erfüllen kann“, o. J. https://esoro.ch/wp-content/uploads/2017/07/051011607_WS_Factsheet_zu_Faltblatt_Lastwagen_207x294mm_D_RZ_161026.pdf.

European Commission. „COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS“, 8. Juli 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301.

———. „TENtec Interactive Map Viewer“. Zugegriffen 29. November 2023. https://ec.europa.eu/transport/infrastructure/tentec/tentec-portal/map/maps.html.

European Council, European Parliament. „DIRECTIVE 2014/94/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 22 October 2014 on the Deployment of Alternative Fuels

Infrastructure“, 22. Oktober 2014. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0094.

———. „DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources“, 11. Dezember 2018. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001.

———. „DIRECTIVE (EU) 2019/1161 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 20 June 2019 Amending Directive 2009/33/EC on the Promotion of Clean and Energy-Efficient Road Transport Vehicles“. Official Journal of the European Union, 20. Juni 2019. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019L1161.

European Environment Agency. „Natura 2000 (vector) - version 2021 revision 1,Oct. 2022“. EEA geospatial data catalogue. Zugegriffen 29. November 2023. https://sdi.eea.europa.eu/catalogue/srv/api/records/dae737fd-7ee1-4b0a-9eb7-1954eec00c65.

European Environment Agency, und European Commission. „CORINE Land Cover“. Zugegriffen 29. November 2023. https://land.copernicus.eu/en/products/corine-land-cover.

European Hydrogen Backbone. „The European Hydrogen Backbone (EHB) Initiative | EHB European Hydrogen Backbone“. Zugegriffen 29. November 2023. https://www.ehb.eu/.

European Parliament, European Council. „DIRECTIVE (EU) 2023/2413 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 October 2023 Amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as Regards the Promotion of Energy from Renewable Sources, and Repealing Council Directive (EU) 2015/652“, 18. Oktober 2023. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202302413.

———. „REGULATION (EU) 2023/1804 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 13 September 2023 on the Deployment of Alternative Fuels Infrastructure“, 13. September 2023. https://doi.org/10.5040/9781782258674.

European Space Agency (ESA). „Copernicus Digital Elevation Model - Copernicus Contributing Missions Online“. Zugegriffen 29. November 2023. https://spacedata.copernicus.eu/collections/copernicus-digital-elevation-model.

Finnish parliament. „Laki ajoneuvo- ja liikennepalveluhankintojen ympäristö- ja energiatehokkuusvaatimuksista“, 15. Juli 2021. https://www.finlex.fi/fi/laki/alkup/2021/20210740.

FuelCellsWorks. „Linde Holds Ground-Breaking Ceremony For New Hydrogen Liquefier In Leuna - FuelCellsWorks“, 31. Oktober 2019. https://fuelcellsworks.com/news/linde-holds-ground-breaking-ceremony-for-new-hydrogen-liquefier-in-leuna/.

Geofabrik GmbH. „Geofabrik Download Server“. Zugegriffen 29. November 2023. https://download.geofabrik.de/europe.html.

Gomoll, Wolfgang. „Brennstoffzellen-Truck im Anmarsch: So fährt sich der Nikola Tre FCEV“, 19. März 2023. https://efahrer.chip.de/news/brennstoffzellen-truck-im-anmarsch-so-faehrt-sich-der-nikola-tre-fcev_1011917.

Greene, David L., Joan M. Ogden, und Zhenhong Lin. „Challenges in the designing, planning and deployment of hydrogen refueling infrastructure for fuel cell electric vehicles“. *eTransportation* 6 (2020): 100086. https://doi.org/10.1016/j.etran.2020.100086.

Guidehouse. „European Hydrogen Backbone Maps | EHB European Hydrogen Backbone“, 2023. https://ehb.eu/page/european-hydrogen-backbone-maps.

H2Mobility. „Overview Hydrogen Refuelling For Heavy Duty Vehicles“, 2021. https://h2-mobility.de/wp-content/uploads/sites/2/2021/08/H2-MOBILITY_Overview-Hydrogen-Refuelling-For-Heavy-Duty-Vehicles_2021-08-10.pdf.

Haskel. „Haskel Website“, o. J. https://www.haskel.com.

Hirschl, Bernd, Lukas Torliene, Uwe Schwarz, Elisa Dunkelberg, Julika Weiß, Clara Lenk, Raoul Hirschberg, u. a. „Zwischenbericht zum Gutachten für den Klimaplan Brandenburg - Erarbeitung einer Klimaschutzstrategie für das Land Brandenburg“. Berlin, Potsdam, Senftenberg, 2022. https://mluk.brandenburg.de/sixcms/media.php/9/ZwBericht-Gutachten-KlimaplanBB_finale%20Fassung.pdf.

Hy-NATuRe. „Hy-NATuRe - Zukunft gestalten mit Wasserstoff“, August 2023. https://hynature.de/abschlussbericht/.

Hyundai. „XCIENT Fuel Cell“, 2020. https://hyundai-hm.com/wp-content/uploads/2020/10/XCIENT-Fuel-Cellcatalog_print.pdf.

Hyzon. „Hyzon Hymax Series“, 2023. https://www.hyzonmotors.com/vehicles/hyzon-hymax-series.

IBERDROLA, CORPORATIVE. „The First 5 Green Hydrogen Storage Tanks Arrive in Puertollano“. Iberdrola, Dezember 2021. https://www.iberdrola.com/press-room/news/detail/storage-tanks-green-hydrogen-puertollano.

Intergovernmental Panel On Climate Change (Ipcc). „Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change“. Cambridge University Press, 22. Juni 2023. https://doi.org/10.1017/9781009325844.

International Energy Agency (IEA). „Energy Consumption in Road Transport in Selected IEA Countries, 2000-2018 – Charts – Data & Statistics“. IEA, 3. Dezember 2020. https://www.iea.org/data-and-statistics/charts/energy-consumption-in-road-transport-in-selected-iea-countries-2000-2018.

IRENA. „Geopolitics of the Energy Transformation: The Hydrogen Factor“, o. J.

———. „Hydrogen: Overview“. Zugegriffen 23. November 2023. https://www.irena.org/Energy-Transition/Technology/Hydrogen.

Karipoğlu, Fatih, Mustafa Serdar Genç, und Beyhan Akarsu. „GIS-based optimal site selection for the solar-powered hydrogen fuel charge stations“. *Fuel* 324 (2022): 124626. https://doi.org/10.1016/j.fuel.2022.124626.

Krieg, Dennis. *Konzept und Kosten eines Pipelinesystems zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff*. Schriften des Forschungszentrums Jülich Reihe Energie & Umwelt 144. Jülich: Forschungszentrum Jülich, 2012.

Latvian parliament. „Grozījumi Publisko iepirkumu likumā Izdarīt Publisko iepirkumu likumā (Latvijas Vēstnesis, 2016, 254. nr.; 2018, 89., 196. nr.; 2019, 41., 45., 253. nr.; 2020, 84.C nr.) šādus grozījumus“, 2. September 2021. https://eur-lex.europa.eu/legal-content/LV/TXT/PDF/?uri=CELEX:72019L1161LVA_202107446.

LBST, Ludwig Bölkow Systemtechnik, und DLR. „H2-Infrastruktur für Nutzfahrzeuge im Fernverkehr Aktueller Entwicklungsstand und Perspektiven“, April 2023.

Leng, Ron, und John Anderson. „Techno-economic analyses“. In *Integration and Optimization of Unit Operations*, herausgegeben von Barry A. Perlmutter, 373–412. Elsevier, 2022. https://doi.org/10.1016/B978-0-12-823502-7.00023-2.

Lubenau, Udo, Hagen Bültemeier, Cruz Marrune, Jens Hüttenrauch, und Philipp Pietsch. „Hydrogen quality in an overall German hydrogen network“, 22. Juni 2022.

https://www.dvgw.de/medien/dvgw/forschung/berichte/g202140-finalreport-h2shortstudy-engl.pdf.

Messaoudi, Djilali, Noureddine Settou, Belkhir Negrou, Soumia Rahmouni, Belkhir Settou, und Ishak Mayou. „Site selection methodology for the wind-powered hydrogen refueling station based on AHP-GIS in Adrar, Algeria". *Energy Procedia* 162 (2019): 67–76. https://doi.org/10.1016/j.egypro.2019.04.008.

NAGas. „DIN EN 17124 Wasserstoff als Kraftstoff - Produktfestlegung und Qualitätssicherung für Wasserstoffbetankungsanlagen zur Abgabe gasförmigen Wasserstoffs - Protonenaustauschmembran (PEM)-Brennstoffzellenanwendungen für Fahrzeuge; Deutsche Fassung EN 17124:2022", o. J. https://www.din.de/de/mitwirken/normenausschuesse/nagas/veroeffentlichungen/wdc-beuth:din21:351617069.

nationalgrid. „The Hydrogen Colour Spectrum", 23. Februar 2023. https://www.nationalgrid.com/stories/energy-explained/hydrogen-colour-spectrum.

NEWA. „New European Wind Atlas", o. J. https://map.neweuropeanwindatlas.eu/.

NOW GmbH. „Genehmigungsleitfaden für H2-Tankstellen", 2022. https://nowgmbh.newshore.de/wp-content/uploads/2022/03/NOW_Genehmigungleitfaden_H2-Tankstellen.pdf.

NOW, GmbH, Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie. „Marktentwicklung klimafreundlicher Technologien im schweren Straßengüterverkehr", Februar 2023. https://www.klimafreundliche-nutzfahrzeuge.de/wp-content/uploads/2023/03/Marktentwicklung-klimafreundlicher-Techn.-im-schweren-Strassengueterverkehr-BARRIEREFREI.pdf.

Paul Nutzfahrzeuge. „PH2P Truck". Zugegriffen 23. November 2023. https://paul-nutzfahrzeuge.de/paul-hydrogen-power-h2-truck/.

Polish parliament. „USTAWA o zmianie ustawy o elektromobilności i paliwach alternatywnych oraz niektórych innych ustaw", 9. Dezember 2021. https://eur-lex.europa.eu/legal-content/PL/TXT/PDF/?uri=CELEX:72019L1161POL_202108377.

PSPA. „PSPA", o. J.

Quantron. „Q-Heavy Quantron", 2023. https://www.quantron.net/wp-content/uploads/2023/06/Q-Heavy_Infobrochure_ES.pdf.

Rose, Philipp. „Modeling a Potential Hydrogen Refueling Station Network for Fuel Cell Heavy-Duty Vehicles in Germany in 2050". PDF. Karlsruhe, 2020. https://publikationen.bibliothek.kit.edu/1000119521.

Rossum, Rik van, Jaro Jens, Gemma La Guardia, Anthony Wang, Luis Kühnen, und Martjin Overgaag. „European Hydrogen Backbone", 2022. https://www.ontras.com/sites/default/files/inline-files/ehb_report_220404_18h00_interactive.pdf.

SAE Mobilus. „SAE Mobilus Website", o. J. https://www.sae.org/.

Schlund, David, Simon Schulte, und Tobias Sprenger. „The Who's Who of a Hydrogen Market Ramp-up: A Stakeholder Analysis for Germany". *Renewable and Sustainable Energy Reviews* 154 (Februar 2022): 111810. https://doi.org/10.1016/j.rser.2021.111810.

Shi, Mengfei, Xingmei Li, und Chuanbo Xu. „Two-stage site selection of hydrogen refueling stations coupled with gas stations considering cooperative effects based on the CRITIC-ITFAHP-MABAC method: A case study in Beijing". *International Journal of Hydrogen Energy*, 2023. https://doi.org/10.1016/j.ijhydene.2023.09.168.

Shiva Kumar, S., und Hankwon Lim. „An Overview of Water Electrolysis Technologies for Green Hydrogen Production“. *Energy Reports* 8 (November 2022): 13793–813. https://doi.org/10.1016/j.egyr.2022.10.127.

SRU. *Wasserstoff im Klimaschutz: Klasse statt Masse*. Stellungnahme. Berlin: Sachverständigenrat für Umweltfragen (SRU), 2021.

Transport&Environment. „Comparison of hydrogen and battery electric trucks“, 1. Juni 2020. https://www.transportenvironment.org/wp-content/uploads/2021/07/2020_06_TE_comparison_hydrogen_battery_electric_trucks_methodology.pdf.

Umweltbundesamt. „Welche Treibhausgasemissionen verursacht die Wasserstoffproduktion?“, 30. November 2022. https://www.umweltbundesamt.de/sites/default/files/medien/479/dokumente/uba_welche_treibhausgasemissionen_verursacht_die_wasserstoffproduktion.pdf.

WEH. „WEH Website“, o. J. www.weh.com.

Wystrach, GmbH, Hrsg. „WyCarrier Datenblatt“, Oktober 2022. https://www.wystrach.gmbh/media/wystrach_wycarrier_datenblatt_de.pdf.

Zemo Partnership. „Hydrogen Vehicle Well-to-Wheel GHG and Energy Study“, Oktober 2021. https://www.zemo.org.uk/assets/reports/Zemo_Hydrogen_Vehicle_Well-to-Wheel_GHG_and_Energy_Study_2021.pdf.

zepp.solutions. „New Hydrogen-Powered Truck: ‚Europa‘ to Launch in Q4 2023“, 7. Februar 2023. https://zepp.solutions/en/new-hydrogen-powered-truck-europa-to-launch-in-q4-2023/.