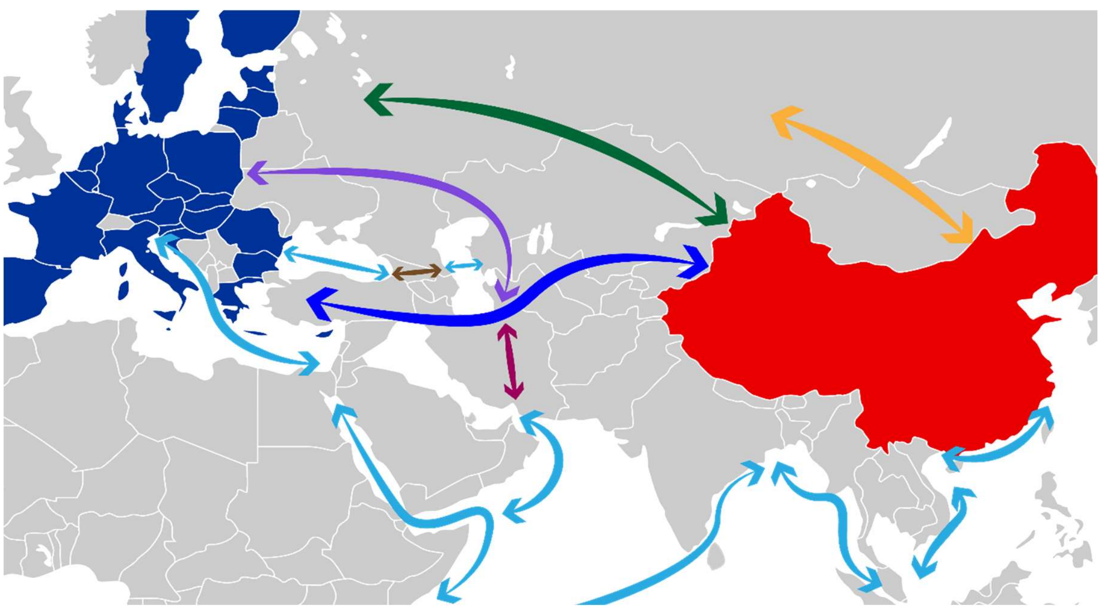
Hydrogen Pre-feasibility and Roadmap Study for Combined Transport via the New Silk Roads to (Central) Asia

(Comprehensive Version)



Management summary

The European Commission's target for 2050 to transform and rebuild energy, heating, electricity and storage as well as transport systems towards zero-carbon builds on hydrogen. Many programs (GreenDeal, Fitfor55) have been set-up and they were reinforced (REPowerEU) due to the energy supply shortage caused by the Ukrainian war. This major effort, comparable to the electrification at the end of the 19th century, requires a whole new green hydrogen business ecosystem to be build.

The 6400-fold volume increase of green hydrogen production from 2021 until 2050[1] as well as the growing range of use of green hydrogen demand major concerted strategy and policy actions to establish, a more robust energy system and sector coupling (electricity, heat, gas, transport, and feedstock use). Through hydrogen, it is feasible to decarbonise areas that are currently not reachable through electricity only. Being and an ideal complement to electrification the hydrogen economy supports (1) the objective of reducing CO2e emissions, (2) diversification of energy sources and (3) increasing the resilience of countries.

Developing the hydrogen business ecosystem is vital to avoid reaching the temperature tipping points that will make the climate on earth's climate change in a non-linear way and irreversible manner. Even if the 2-degree warming objective of the Paris agreement is met, it could be too late to prevent the harmful effects of some regional tipping points (e.g. corral reefs)[2].

Despite the urgency and importance of the green transformation, the rail sector and especially combined transport as one of the most environmentally friendly transport modes are not yet actively a part of building the infrastructure to support the extended green hydrogen economy. While hydrogen as fuel is gaining prominence in rail and road studies and pilots the focus of this pre-study is on the little analysed transport of hydrogen as tradeable good via combined transport.

This study explores the **pre-feasibility** of combined road-rail transport in playing an important role in the new hydrogen business ecosystem building effort worldwide to reduce fossil fuel consumption. While it covers EU-internal shipments the focus is on imports from Central Asia as part of the Living Lab 2 Use Case 2 of the EU-funded Planet project.

One objective of Planet Use Case 2 is to explore growth opportunities on the New Silk Roads. Secondly, we draft a development **roadmap** on the sequencing of the required changes as well as the prerequisites to foster a successful transformation. The report, thereby, lays the initial foundations regarding the way forward to identify where and how combined transport can be part of the green hydrogen economy. It is important here to note that most hydrogen reports either fail to analyse combined road-rail transport (e.g. IAE 2022) or foresee it only in the destination country[3]. However, comprehensive coverage of all related aspects is not the

[1] IRENA (2022) "Hydrogen Overview" https://www.irena.org/Energy-Transition/Technology/Hydrogen with a 10% variance

[2] Reaching certain tipping points may trigger a cascade of other tipping points due to significant inter-dependencies as some scientists state: Armstrong McKay et al. (2022) "Exceeding 1.5°C global warming could trigger multiple climate tipping points", SCIENCE, 9 Sep 2022 Vol 377, Issue 661; OECD (2022) "Climate Tipping Points Insights for Effective Policy Action", OECD Publishing; Kemp, Luke et al. (2022) "Climate Endgame: Exploring catastrophic climate change scenarios" PNAS (119)

[3] e.g. Guidehouse 2022, IRENA 2022 "Covering Germany's green hydrogen demand: Transport options for enabling imports", IRENA (2022) "Global Hydrogen Trade to Meet the 1.5 Climate Goal, Part 1"

purpose of this prefeasibility study. The focus here is to identify and assess only the most relevant scenarios.

The study builds on existing hydrogen reports, project experience from the authoring companies and 10 expert interviews from selected hydrogen business ecosystem participants to provide a sound and up-to-date development status and include the outlook of the industry experts.

The study starts with an introduction of the hydrogen opportunity for combined transport and the need for action complemented by the political setting. This is followed by a short deep dive into the specific characteristics and challenges of hydrogen and its development outlook.
In chapter 2 the global hydrogen business demand is broken down into EU's share and hydrogen uses to derive likely customer groups and estimated hydrogen and hydrogen derivate consumption. Despite many earlier reports, establishing a sound customer demand basis for the roadmap development required considerable effort.

Chapter 3 identifies the current gaps in the offering of combined transports to explore the status of the solution elements. A short overview of the existing equipment and alternative transport modes (chapter 4) lays the basis for the definition of future development scenarios on the New Silk Roads and supporting funding opportunities (ch. 5). The study contains a qualitative risk assessment of the path towards building a green hydrogen business ecosystem with combined transport services. Chapter 6 combines the feasibility assessment with the proposed roadmaps (2030 and 2040) for the selected Central Asia routes as part of the New Silk Roads.

The study closes with first indicative recommendations for each stakeholder and some recommendations for next steps and future opportunities towards pushing resilience and decarbonisation highlighting combined transport's role supporting the effective building of a sector coupling enabling hydrogen business and private ecosystem. Attention is given to the flexibility and resilience of the existing rail infrastructure with existing or extended terminal infrastructure to generate new business opportunities on the New Silk Roads.

Key Findings and recommendations are:
Hydrogen transport on rail is underdeveloped and seemingly untested in the countries that have been deeply analysed. Transport of hydrogen from a technical, safety and cost-efficiency view is a key element to ensure that the investment in the production and supply is not at risk. To support Europe to reach the decarbonisation objectives a multi-modal and green transport mix is required to ensure the resilience in case of major disruption and efficient use of the existing infrastructure.

We identified some hydrogen supplies that will rely on rail transport, but the most efficient form of transport is yet not fully determined and explored as it depends on the customer needs. Customers seem to be hesitant to start long term commitments.

Therefore, there is an urgent business need to test and validate the practical requirements and operational maturity of hydrogen for combined transport to reduce the risk of stranded assets and investment. On the opportunity side it will enable early standardisation and ensure interoperability as well as a solid basis for a ramp-up planning.

The business case is at risk for combined transport in case of a lack of concerted action between the relevant players. If the chicken-and-egg blockage lingers the needed innovation, standardisation and interoperability will not materialise in time to significantly contribute to climate targets.

From the experience of other crises (e.g. Covid-19 pandemic-related supply challenges) we recommend out-of-the box thinking (logistically, regulatory, and IT-related) and exploration of parallel activities to win time despite the fact that rail-based transport is not known to be at the forefront of business dynamics and innovation. The role of combined transport in developing a hydrogen business-private ecosystem can be significant if a sufficient momentum of powerful business-public ecosystem members can be raised leading to meaningful actions.

The **business ecosystem** for hydrogen and ammonia shipments via rail is still at its infancy. Both commodities can be shipped via rail with existing technologies. Especially hydrogen will require significant investment and funding to become competitive through standardisation, interoperability, cost-down and innovation.

Further analysis is required to address whether only ammonia or also simultaneously hydrogen will be used for long-distance and short-distance shipments via rail and road. However, we foresee that both will be required and demanded from a consumer perspective in the future. Therefore, technology openness can be recommended to explore both forms of hydrogen transport further and start with the practical implementation pilots soon. Only then the time-lag can be avoided if the demand scales-up fast in the period from 2026 to 2035. For the New Silk Roads, the existing investments might not be enough to facilitate the expected future traffic. In the short term, the study provides additional motivation to **put up most energy into modernising and capacity increase** of the available New Silk Road corridors.

The study shows that combined transport is a possible way to **enable the energy ecosystem transition towards a hydrogen-based economy**, and in the process increase not only the robustness and resilience of energy and feedstock supply in many areas in the future but also help **achieve the climate goals simultaneously**. We elaborated a roadmap for business ecosystem transformation that is required to establish this alternative.

The detailed implementation planning, standardisation and interoperability decisions and choices on technology specifics need to be performed in further detailed studies. The current state of development offers too many options to qualify as a sound investment basis. The first practical experience is mandatory to lay a sound decision basis for the **private sector** and future **policy basis for regulators**. The initial steps have been well-prepared. It is critical now to overcome the chicken-and-egg complacency by fostering sector encompassing innovation and implementation into the interoperability and efficiency of a hydrogen economy as key element of a decarbonised flourishing and competitive European economy.

It is a seemingly tantalous task, but a greener and more robust economy will not only help the business but also the social side and environment, thereby turning a vicious circle into a virtuous one. Dedication of time, funds, ideas and common motivation is needed to avoid the catastrophic case scenarios[4] and materialise in the best possible transparent collaborations.

[4] Luke Kemp et al. (2022) "Climate Endgame: Exploring catastrophic climate change scenarios", PNAS

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Acknowledgments:
The study was conducted by Consilis and Theron in close cooperation with UIRR (International Union for Road-Rail Combined Transport s.c.r.l.). Financing by EU Planet project is gratefully acknowledged. In addition, we thank the ICP members and many hydrogen stakeholder interviewees for the fruitful discussion and contribution.

0 Abbreviations

AEM	Anion Exchange Membrane (Electrolyser)
ALK	Alkaline (Electrolyser)
CAGR	Compound Annual Growth Rate
CCS	Carbon Capture and Storage
CFC	Chloroflourocarbons
CO_2e	CO_2 equivalent
CT	Combined Transport
CTO	Combined Transport Operator
BEV	Battery Electrical Vehicle
EC	European Commission
EU	European Union
GHG	Green House Gas (heat absorbing atmosphere gases CO_2, CH_4, O_3, H_2O, N_2O)
HGV	Heavy goods vehicle
HRS	Hydrogen Refuelling Station
IM	Infrastructure Manager
ICE	Interna Combustion Engine
ICP	Intercontinental Collaboration Platform
cH2	compressed Hydrogen
lH2	liquid Hydrogen
HBE	Hydrogen Business Ecosystem
H2 / H_2	Hydrogen (chemical formula)
HNO	Hydrogen Network Operator (pipelines)
HFC	Hydrofuorocarbons
$LCOH_2$	Levelised cost of hydrogen
LOHC	Liquid Organic Hydrogen Carrier
LHV	Lower Heating Value
Mt	Million tons (Mega tons)
MW	Mega Watt
MWh	Mega Watt hour
NH_3	Ammonia
PJ	Penta Joule
PEM	Proton Exchange Membrane (Electrolyser)
P2G	Power-to-Gas
RFNBOs	Renewable Fuels of Non-Biological Origins
RU	Railway Undertaking
SOEC	Solid Oxide Electrolyser Cell
TO	Terminal Operator
UIRR	International Union for Road-Rail Combined Transport

1 Purpose and motivation

The initial idea for this study was generated and revised in the context of building the Intercontinental Collaborative Platform. It consists of combined transport (CT) operators and invited LSPs and shippers on the New Silk Roads. The open platform was formed as part of the EU-funded Planet project[5]. During the ICP discussions shipping hydrogen was identified as one of the future growth areas for import to Europe on rail for landlocked countries in Central Asia. This led to the decision to explore this topic in a pre-feasibility and roadmap study with ICP members contributing.

The purpose of the CT green hydrogen feasibility and roadmap pre-study is threefold:

1) Explore the **pre-feasibility** if shipping hydrogen can be a new business for combined transport and to identify the potential of the status-quo of the nascent hydrogen business ecosystem (HBE) of producers of hydrogen, service providers, and equipment as well as customer demands. The volume growth of green hydrogen in an ambitious scenario is projected to increase from less than 1 Mt in 2022 to more than 100 Mt in 2050 to foster the decarbonisation within Europe and globally.
2) Explore the need of hydrogen as fuel for the European rail industry and the impacted transport modes and more importantly as good to be transported for other industries.
3) Identify the hurdles and forecast the conditions and measures for a **roadmap** towards a future state where Combined Transport can be part of the solution to support a hydrogen business ecosystem as key element to successful green energy transition.

The motivation is to assess if hydrogen and its derivates can be transported via road-rail efficiently and identify bottlenecks that need to be addressed. The initial hypothesis was that most green and robust form of transport should be part of the new resilient future green energy and feedstock supply for Europe.

Why only a pre-feasibility study: The many variables on a long transport path, the transport means and customer needs do still not allow to undertake a thorough bottom-up or top-down assessments. This pre-study aims to contribute to laying the foundation for more detailed research and pilot project implementations. We highlight the gaps and conditions to make the transition happen with many concerted actions between policy makers, associations, industry and logistics service providers along the New Silk Roads. The pre-study brings clarity where combined transport will be a viable complement and what favourable preconditions are.

In the given scope of the study the authors were not able to give a full account of CO_2 impact of hydrogen transport due to the challenges in conducting a comprehensive assessment via existing tools for Central Asian relations. This sobering finding raises the relevant need to produce these tools and measure real transport routes on a detailed level to avoid decisions based on wrong or misleading values. A second limitation is that cumulative Green House Gas (GHG) emissions and NOx were not comprehensively evaluated as they are underrepresented in most reports and studies. This needs undoubtedly to be included in future work. Thirdly, renewable energy and production of green hydrogen is not discussed in detail here.

[5] www.planetproject.eu

2 Hydrogen business opportunities for combined road-rail transport

2.1 Prologue: Why now hydrogen as a solution?

"Water decomposed into its primitive elements (..) by electricity, which will then have become a powerful and manageable force. (..) Water will one day be employed as fuel, that hydrogen and oxygen which constitute it used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable"[6]

Surprisingly the novelist Jules Verne has predicted the future potential of hydrogen in his book from 1874 – now more than 149 years ago. Not only the substitution of fossil fuels as source of heat but also as power and feedstock make it uniquely qualified as universal and environmentally friendly source compared to many alternatives.
The potential was long there with considerable progress, but large-scale use of green hydrogen (CO_2e free produced)[7] is only reachable now due to several factors that demand for fast progress of a large-scale business ecosystem transformation:

1) Availability of **low-cost green energy** (esp. via solar photovoltaic power prices for 1 kg H_2 can fall below 1 USD in favourable regions of the world in 2050[8])
2) Pressure to **decarbonize** the industry and private consumption to reduce the impact of climate change
3) Growth of **electrolyser start-ups** and more research intensity in recent 5 years
4) **Fast transition** from Russian gas and oil sources leading to higher priced substitutes
5) Realistic opportunity to achieve **sector coupling** to increase resilience levels due to its conversion and cost-efficient storage capabilities[9] and avoidance of renewable energy shut-downs due to missing demand or grid capacity and thereby increasing the efficiency of the total energy system

These arguments justify a recent re-evaluation of the previously too expensive green hydrogen as viable solution element for the whole global energy supply but also for decarbonising the transport sector.

Hydrogen as energy source is also not new as it has been used in Britain as coal-gas to heat some villages until 1950[10]. Widely used gasification of coal was used as city gas (a mixture of hydrogen, methan, carbon monoxide and nitrogen) in Vienna, Berlin or New York. It was successively substituted by methane after Second World War[11].

Significant amounts of hydrogen are already consumed in present industrial uses. However, the hydrogen is produced from natural gas and will need to be decarbonized. There is already

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[6] Jules Verne (1874) "The Mysterious Island", New York or https://www.gutenberg.org/files/1268/1268-h/1268-h.htm

[7] Green hydrogen is CO_2 equivalent free produced using renewable energy sources only. The transport of it is intended to be as green as possible and will be addressed later in this study.

[8] IAE (2022) "Global Hydrogen Review 2022" p. 94

[9] Steiner, M; Specht, M (2021) "Power-to-Gas and Power-to-X: The history and results of developing the new storage concept"

[10] Alvera (2021) "The Hydrogen Revolution – The Future of Clean Energy"

[11] https://de.wikipedia.org/wiki/Stadtgas

grey or black hydrogen use of liquid H2 in space travelling since 1960s and in for more than a century in high volume chemical processes (fertilizers and petrochemicals).

One counterargument against the green hydrogen transformation fearful: There are risks which we will address (see ch. 7), but the Zeppelin disaster of 1925 is not a valid counterargument against hydrogen anymore due to the high level of safety measures applied by the key gas producing and supplying companies. The Zeppelin disaster would not happen today with existing knowledge, safety standards and measures in this form[12]. The common fear in the public of hydrogen-air explosiveness however must not be underestimated. Another often used counterargument is the energy efficiency. This argument alone is misleading, the efficiency can still be optimised in many contexts, and it is far better than many of today's energy supplies that contribute to the climate crisis (e.g. fossil fuels).

In a nutshell the hydrogen situation can be described as:

- Known and controlled technology
- Green hydrogen production is in its maturing phase depending on chosen technology
- Distribution structures for hydrogen already exist (e.g. regional hydrogen networks in Europe) and have been operated without incidents for decades
- Innovation is a function of the money spent (e.g. progress of automotive, computer chip or photovoltaic cell industry in the last century demonstrated large progresses)

Hydrogen is considered as a salient element accounting for 10% of the future CO_2 reduction as forecasted by IRENA by 2050. Today green hydrogen achieves only 0.02% of the target and the build-up needed for the whole business ecosystem is large to achieve the goal (see Figure 1).

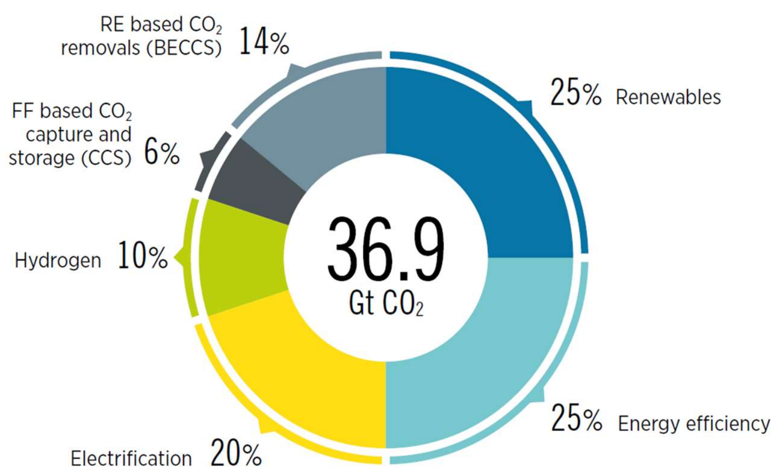

Figure 1: Reducing emissions by 2050 through six technological avenues (Source: IRENA, 2022)

Europe's target is to reduce 560 Mt of CO_2 by 2050 by using green hydrogen[13] to achieve a 2-degree scenario. Including feedstock, the final energy demand for green hydrogen in Europe is targeted at about 24% share. For the 1.5-degree scenario CO_2e reduction achievements need to be even larger. It is without question that the measures are known but current policies need

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[12] Alvaro (2021), "The Hydrogen Revolution – The Future of Clean Energy"

[13] FCH (2019) "Hydrogen Roadmap Europe – A sustainable pathway for the European energy Transition"

to be extended and require implementation without delays in the next two decades as the recent IPCC report stresses[14]. Without CO_2 and GHG emission reduction, the risks of cost escalation for humans, stranded assets and the natural ecosystem losses are higher than implementing the measures as also non-climatic risks will increase and interact.

2.2 Urgent need for action to green energy consumption in transportation and transport of energy

There is little doubt that more than 95% of the global energy need can be theoretically satisfied with already existing carbon-neutral technologies while creating more jobs in 145 countries by 2030[15]. Several studies show the (potential) feasibility of a 100% renewables energy system[16]. With green energy being a reachable prerequisite towards the zero-carbon emission, use of hydrogen as resilient complementary green energy vector is a valid option in a future carbon neutral energy system[17]. With the production (see ch. 3.3) and transport (see ch. 4.1) challenges to be solved in the next 6-8 years the application area of transport becomes a key building block on the path towards a working and affordable hydrogen business ecosystem to play an important role to substitute the existing fossil dominated present world of transportation. In this study we will lay out the motivation for this enormous substitution and transformation effort.

2.2.1 Hydrogen as source for propulsion energy

At the TRA in Lisbon in November 2022 Prof. McKinnon elaborated that the transport industry is very likely to fail to achieve its targets set by the EU commission (Fit-for-55), the overall commitment to the COP goals, and the Paris Climate Agreement (below 2°C temperature rise above preindustrial levels). The gap including existing and additional measures will still persist for 2030 and 2050. CO_2 capturing is likely to be an additional high energy consuming last resort option that is a too risky bet as a one fits all solution[18].

[14] IPCC (2023) "Synthesis Report of the IPCC Sixth Assessment Report"

[15] Jacobson, Mark et al. (2022), "Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries", in Energy and Environmental Science, 15, 3343-3359

[16] E.g. Breyer, Christian (2022), "On the History and Future of 100% Renewable Energy Systems Research", IEEE Access, 10, 78176-78218

[17] Steiner, M and Specht, M (2021) "Power-to-Gas and Power-to-X: The history and results of developing the new storage concept" and H_2 applications

[18] Prof. McKinnon, Alan (2022), "Innovative Concepts and Services for Zero-emission Mobility of People and Logistics", Transport Research Arena (TRA) Conference, Lisboa, 15.11.2022

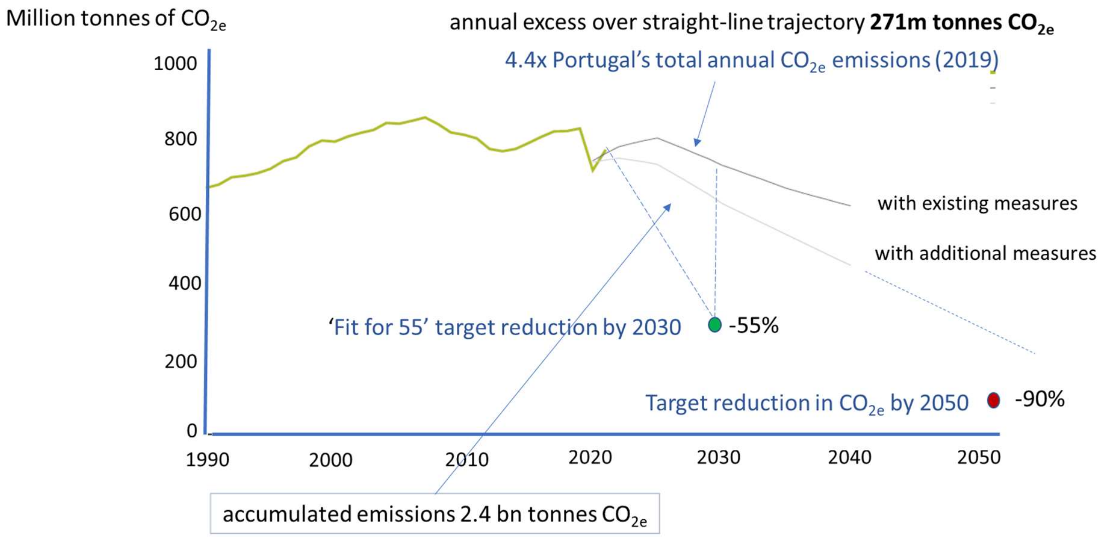

Figure 2: EU's forecasted failure to meet targets (McKinnon, TRA Lisbon, 15.11.2022)

Adding the need for action is a fact. The transport industry is the only industry in the EU that increased its CO_{2e} emissions in the period 1990-2020[19] and is today responsible for about 25% of the EU CO_{2e} emissions.

Hydrogen is required for many transportation modes and especially for rail if (1) electrification is less cost-efficient or (2) electrification will take too long, or (3) batteries are not supplying sufficient performance or refilling times[20].

The transport sector is not set to meet the required goals and needs to work on closing the future goal achievement gap without increasing costs and risks to a level that will prohibit the competitiveness of Europe (see Figure 3).

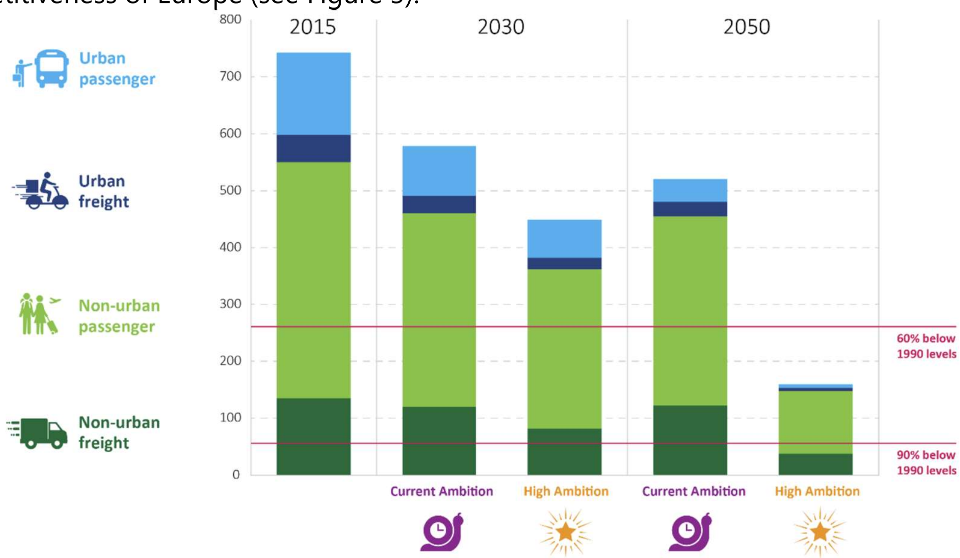

Figure 3: Total emissions by transport sector and scenario in Europe [Mt CO_2] [21]

[19] McKinnon, TRA Lisbon, 15.11.2022 (Sources: Eurostat and European Environment Agency)

[20] Chamaret, Ap et al. (2022) "Analysis, trends and expectations for low carbon railway"; TRA Lisbon 2022

[21] OECD/International Transport Forum (2001) "Decarbonising Transport in Europe – The Way Forward"; http:/bit.ly/3O4W0vW

In order to close the gaps 6 decarbonisation levers[22] need to be diligently applied:

Lever	Measures	Time line
1. Reduce transport demand	Remote work, circular economy, digitalization, 3-D printing, local sourcing	Short to medium term
2. Foster modal shift to lower carbon transport modes	EU Sustainability and Smart Mobility Strategy[23]: Increase rail freight by 50% (2030), increase by 100% (2050). 21% of rail freight tonnage was fossil (2020); road share ca. 75% (2010-2020).	Medium to long
3. Optimise capacity utilisation	Digitalisation and optimisation measures support, but share of empty runs still around 20% (2020)	Short to medium
4. Increase energy efficiency of transport	1) Rising fuel economy, 2) training for drivers, new and more efficient cars and trucks, 3) telematic monitoring lead to 5% reduction of 28-33% truck efficiency potential (TNO)	Short to medium
5. Reduce carbon content of transport energy	Increase effort towards zero emissions measures in all modes, but disagreement / uncertainty over renewable energy options hinders progress	Short to medium
6. Incentivise green energy transport capabilities and change taxation	Full integration of transport sector into CO_2 trading regime (incl. CO_2 pricing[24]) and selected facilitation of transformation towards more electric and hydrogen-based transport modes; equalise energy taxation of rail, aviation and waterways with road	Medium to long

Figure 4: Overview of decarbonization measures[25]

2.2.2 Undervalued: Hydrogen road-rail supply chain to transport and store energy

Next to the use of hydrogen as energy source for propulsion this pre-study we will mainly focus on the area highlighted in orange that describes the currently missing option of shipping hydrogen in large scale via rail (see Figure 6). The sources of carbon-free energy are multifold and not limited to wind and solar only. Low carbon hydrogen can be generated from not fully green sources such as biomass and energy from waste and from fossil fuels in combination with carbon capture storage and use. These sources are required to complete the available energy spectrum to scale up the supply. On top of this nuclear energy source-based hydrogen (pink) is considered as an option in some countries. For the ramp-up phase up to 2030 some fossil based (black) hydrogen may be required to path the way towards a carbon zero scenario in 2050.

The coloring schema discerning the energy sources to produce hydrogen is widely used to differentiate the degree of how CO-free hydrogen is:

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[22] Adapted from Prof. Mc Kinnon, Alan, "Innovative Concepts and Services for Zero-emission Mobility of People and Logistics", TRA Lisbon, 15.11.2022

[23] See GIZ overview: https://www.changing-transport.org/wp-content/uploads/EU-Mobility-Strategy.pdf

[24] https://www.euractiv.com/section/emissions-trading-scheme/news/eu-agrees-co2-tax-on-heating-and-transport-fuels-softened-by-new-social-climate-fund/ (accessed 10.01.23)

[25] Adapted from Mc Kinnon, Alan "Innovative Concepts and Services for Zero-emission Mobility of People and Logistics", TRA Lisbon, 15.11.2022

Group	Color	Source	Production 2020 (world)	Forecast 2050 (world)	Growth (CAGR)
Fossil based	Black/ brown	From coal	<1 mt	----	
Fossil based	Grey	From natural gas (steam reforming)	117 mt plus 48 mt as byproduct	?	
Fossil based / „Climate neutral“ (more or less)	Blue	From natural gas plus carbon sequestration (CCS)	0.6 mt	80 mt	17.7%
„Climate neutral“ (more or less)	Green	Produced with renewable electrity (solar, wind, etc.)	1.2 mt	160 mt	17.7%
„Climate neutral“ (more or less)	Turquoise	From natural gas through methane splitting and permanent removal of solid carbon	----	?	
„Climate neutral“ (more or less)	Purple/ pink/ red	Produced with nuclear energy	----	?	
			ca. 168 mt	**> 250 mt**	1.3%

Figure 5: Hydrogen colors and volume development[26]

It may be required to use all hydrogen origins to support the growth and the build-up of the green hydrogen business ecosystem even if only the conservative demand for 2050 is targeted.

Pure hydrogen subsumes various levels of compression and conversion to other energy vectors such as ammonia (NH_3) or other transport media (e.g. Liquid organic hydrogen compounds (LOHC) or metal hydrids)). Of the hydrogen applications the energy supply to support the propulsion of trains deserves special attention because of the mutual interdependency of supply of hydrogen and its use as fuel to propel trains in areas where no green electrification is economically possible. It can serve two purposes: (1) hydrogen as tradeable good to be shipped and (2) an input factor for the combined transport industry. This study focuses on hydrogen as good to be shipped but will mention positive synergies with hydrogen as fuel where possible.
The energy sources for hydrogen are multifold such as the distribution methods and uses (see Figure 6). This pre-study focuses on the exploration of the dotted line for the train-based shipments in combination with road transport for the last mile (about 50-70 km) to the final recipient. This area lacks research and practical implementation due to the current dedicated use of hydrogen mainly in the petro-chemical and fertilizer industry sectors.

[26] www.statista.com offers different sources and the range is between 250 mt to 660 mt (Global hydrogen demand forecast by region 2030-2050) (10.01.23)

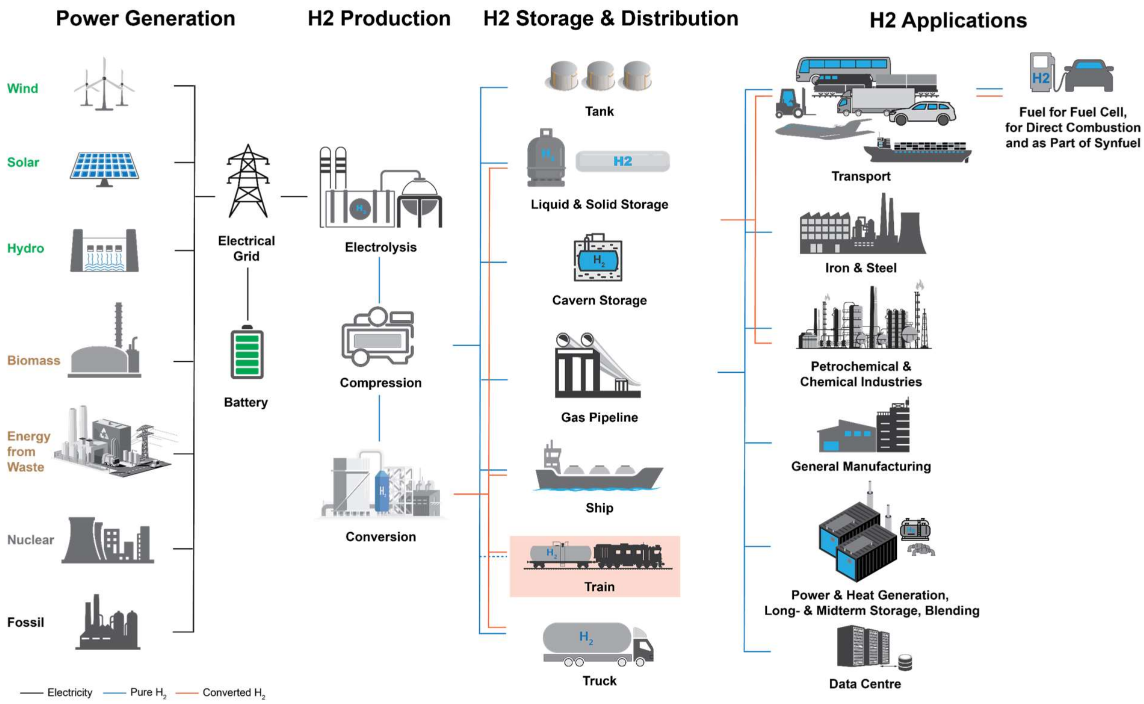

Figure 6: Hydrogen Business Ecosystem and its transformation (own source)

The investment planning from IRENA focuses on ships and pipelines (see Figure 7), which seems to ignore last mile distribution (trucks) and alternative modes of transport (road-rail CT).

Note: Area is proportional to the investment in the respective part of the value chain, with the total area adding up to USD 3 960 billion. The cost of conversion plants includes storage and terminals costs and refers to both conversion and reconversion from or to hydrogen. The results are from this analysis.

Figure 7: Investment into hydrogen business ecosystem from 2020-2050[27]

[27] IRENA (2022a), Global hydrogen trade to meet the 1.5°C climate goal: Part I – Trade outlook for 2050 and way forward, International Renewable Energy Agency, Abu Dhabi.

2.3 Political frameworks for a H_2 business ecosystem revolution

2.3.1 Global: Present and Future Outlook until 2050

The ubiquitous potentials of renewable energy production leading to the emergence of additional geographic locations with high potential for renewables that were not on the world map of energy production until recently, has prompted the stakeholders of the sector to be in a constant state of search for cost-effective solutions to enhance the viability of renewables, and, in the process, expedite and entrench 'green transition'. This arduous exercise has been leading to an increasing focus on hydrogen. The chemical element's energy-carrying strength has enormous decarbonization potential as it can enable substantial cross-border renewable energy trade[28] and large long-term energy storage capacities unlike many other energy storage alternatives.

In the backdrop of the goal to limit global warming to significantly under 2°C for meeting the 2015 Paris agreement[29], the aggregate annual global hydrogen demand is expected to touch 614 Mt by 2050 to meet the 1.5 °C scenario according to IRENA[17]. It is vital to ensure compatibility of hydrogen markets with electricity and carbon markets to avoid double incentives or transfer of certificates. Consistent carbon pricing in all sectors will result in a competitive advantage for the use of emission-free hydrogen.

A carbon price level average of US $173/tonne CO_2 is needed to meet a 50% reduction in GHG emissions by 2050, while a carbon price level average of US $191/tonne CO_2 to achieve a close to 100% decarbonisation[30]. Industry proponents like shipping line Maersk demand US$ 150/to CO_2 which is close to the lower level[31]. The idea is to encourage consumers and industries to adopt viable alternatives on account of the rising fossil fuel prices following an increase in carbon prices based on fossil fuel consumption or GHG/CO_2 emissions, which are set directly by regulators or developed as a result of mandatory emission trading systems.

Many countries or supra-national organisations[32] are developing hydrogen strategies of which the following sections summarise key facts for a relevant selection of countries.

2.3.2 Regional: EU Regulations and Future Outlook

With technologies being constantly updated and the market still in its nascent stage, regulating hydrogen is in its evolutionary stages across the world and Europe is no exception. These regulatory uncertainties and ambiguities are adding to costs in terms of higher risk premium for projects. The Delegated Acts, which are non-legislative and legally binding in nature, and aimed at supplementing or amending non-essential elements of EU laws, are among the routes

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28 IRENA (2022a), Global hydrogen trade to meet the 1.5°C climate goal: Part I – Trade outlook for 2050 and way forward, International Renewable Energy Agency, Abu Dhabi.

29 https://unfccc.int/sites/default/files/english_paris_agreement.pdf. The stricter 1.5 degree warming goal was not agreeable with all participants.

30 Baresic, Domagoj et al. (2022) "Closing the Gap: An Overview of the Policy Options to Close the Competitiveness Gap and Enable an Equitable Zero-Emission Fuel Transition in Shipping. Prepared by UMAS, London. The authors state that the carbon price level increases to 264 USD (-50% CO2) and 360 USD (close to carbon-zero) respectively.

31 Berit Hinnemann (2021) (Head of Decarbonization Business Development at Maersk) "Methanol vs Green Ammonia" in ARGUSMedia Conference "Methanol vs. Green Ammonia: The future of marine fuels (07-09.12.21)

32 E.g. World Economic Forum (2023) "Accelerating Clean Hydrogen Initiative" https://initiatives.weforum.org/accelerating-clean-hydrogen-initiative/home (0

through which renewable fuels of non-biological origin (RFNBO) are regulated. The European Commission renewable energy directives form the renewable energy legal framework (incl. RePowerEU plan) across the EU member countries.

However, recently, the European Parliament in effect did away with the Delegated Act 'additionality' requirements for certifying hydrogen as 'renewable'. This gave hydrogen producers some flexibility in sourcing electricity from the grid and more time for offset with dedicated supply[33]. The revised new approach is to ensure an overlap between hydrogen production and renewable energy production only on a quarterly instead of an hourly or daily basis as demanded by some activists[34].

The move to do away with overly restrictive regulations is aimed at encouraging greater hydrogen production in Europe to accelerate its decarbonisation efforts. It came following concerns that the Delegated Act could lead to companies in the hydrogen industry shifting to the US that had announced huge tax credits for green hydrogen production[35]. It recognizes the fact that hydrogen is not only a product produced from green energy but an essential means of storage and transportation of carbon free energy, a fact was initially undervalued.

EU makes some efforts to promote the hydrogen supply growth in neighbouring countries[36] but some questions remain to be answered such as specification and certification of green hydrogen from other regions of the world.

The Net-zero Industry Act is a response to Inflation Reduction Act (IRA) by the US government. It was first announced in Davos on 19th of January and communicated on the first of February 2023 to counterbalance tax credits and the lower energy prices in the US. First elements will be enacted in 2023 and new rules to accelerate the transformation by 2025[37].

2.3.3 Regional: Central Asia's hydrogen strategies

The Central Asian region, endowed with substantial renewable energy resources, has huge potential to develop as a green hydrogen hub. However, water scarcity has been identified as a major challenge in this context in the region[38]. One of the countries taking the lead is Kazakhstan, which has abundant wind throughout the year. The country has entered into agreements with the European Union on batteries, renewable hydrogen and raw materials to be a stable green hydrogen supplier to the EU[39]. Germany has announced the setting up of a

[33] Changed from just an hour in the Delegated Act to a quarterly basis till 2030 and then as per the European Commission's decision. Further the additional requirements on the location of hydrogen production in proximity of a renewable energy production will be removed until end of March 2028.

[34] Kurmayer, N.J., 2022. LEAK: Long-awaited EU rules on renewable hydrogen expected 15 Dec. Euractiv. 5 December. https://www.euractiv.com/section/energy/news/leak-long-awaited-eu-rules-on-renewable-hydrogen-expected-15-dec/

[35] Parkes, R. (2022) "Scrapped | EU's controversial 'additionality' rules for green hydrogen are history after European Parliament vote" Recharge. 14 September.

[36] European Commission (2020) "A hydrogen strategy for a climate-neutral Europe" COM(2020) 301 final, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0301&from=EN

[37] https://www.hydrogeninsight.com/production/eu-to-offer-fixed-premium-to-green-hydrogen-producers-in-attempt-to-compete-with-us-h2-tax-credits/2-1-1397068

[38] UN (2022) "UN system supports countries in Central Asia to build resilient energy systems" UNECE. 16 November

[39] Shayakhmetova, Z. (2022) "Kazakhstan Seeks to Develop Green Hydrogen, Accelerates Energy Transition" The Astana Times. 29 November.

'hydrogen diplomacy' office in Kazakhstan[40]. The geographical location on one of the Middle Corridor of the Silk will make this region central to our study.

2.3.4 National: EU Member State example Germany: Present and Future Outlook

Germany established its national hydrogen strategy in June 2020, which aims at the decarbonization of industries, transport, and energy generation through the application of hydrogen technologies. The main goals that have been set in the strategy are monitored on a regular basis and are supported by a national hydrogen council that includes scientists, industry representatives and politicians. The seven goals of the hydrogen strategy[41] are (a) to establish a regulatory framework for hydrogen markets, (b) to build up production capacities for hydrogen and hydrogen derivatives, (c) to establish an infrastructure for the hydrogen value chains including hydrogen fuelling stations, (d) to improve the competitiveness of hydrogen and hydrogen derivatives, (e) to achieve decarbonization of industry and transport through the use of hydrogen, (f) to position German as a leading supplier in the field of green hydrogen production and its application technologies, (g) to establish international cooperation (within and outside the EU) with regard to hydrogen import and hydrogen technology exports.

The launch of Important Projects of Common European Interest (IPCEI) is integrated into the national hydrogen strategy. They include (among others) electrolysis projects with a capacity of over 2 GW and 1,700 km of hydrogen pipelines, which are scheduled to be in operation by 2028. In addition to the national hydrogen strategy, most German federal states have developed their own hydrogen strategies, the most extensive of which is the state of Northrhine-Westphalia's (NRW) that sets ambitious quantitative goals[42]. In the area of transportation these include 400 fuel cell trucks, at least 20 truck hydrogen refuelling stations and 60 hydrogen refuelling stations for passenger cars, 500 hydrogen powered buses and first hydrogen powered inland ships – all by 2025. NRW also plans 120 km of hydrogen pipelines in NRW with connections to transregional (Dutch, Belgian) hydrogen pipelines until 2025 and 240 km until 2030. It will install more than 100 MW electrolysis capacities for industrial hydrogen production by 2025, and up to 3 GW until 2030. A first demonstration plant to produce synthetic fuels and raw materials from hydrogen is planned in the Cologne/Wesseling industrial area. Also, hydrogen-based steel production is to be expanded and hydrogen-based plants are to be introduced in glass, tile and brick industries and in foundries until 2030. Some of these goals are more ambitious than the overall national goals. Therefore, it can be assumed that the aggregated goals of all federal states will be well above the national target goals.

2.3.5 National: USA current hydrogen regulations

The US aims to achieve an annual clean hydrogen production of 10 million mt by 2030 and ensure that clean hydrogen cost by electrolysis is $1 per kg by 2031. It is also considering establishing over four regional hydrogen hubs[43]. The US launched in August 2022 the Inflation

[40] Putz, C. (2022) "Germany Eyes Green Hydrogen Potential in Kazakhstan" The Diplomat. 2 November

[41] Bundesministerium für Wirtschaft und Klimaschutz (BMWK) (April 2022) „Fortschrittsbericht zur Umsetzung der Nationalen Wasserstoffstrategie"

[42] Ministerium für Wirtschaft, Innovation, Digitalisierung und Energie des Landes Nordrhein-Westfalen (Oktober 2020), „Wasserstoff Roadmap Nordrhein-Westfalen"

[43] Morgan Lewis (2022) "Draft DOE National Clean Hydrogen Strategy and Roadmap Details Opportunities in Hydrogen Sector"

Reduction Act (IRA) that contains 369 billion USD support for energy security and climate change. The target is to lower carbon emissions by 40% in 2030 and support US-based green technology investment through significant tax credits[44].

The US recently announced tax credits for 'qualified green hydrogen'. From 2023, producers of such hydrogen will be able to avail up to $3 per kg depending on the wage standards and GHG emissions. The Green Hydrogen Standard is the basis for green hydrogen project certification, and a maximum of 1 kg CO_2e per kg hydrogen is allowed for green hydrogen projects[45]. Together with Canada and Mexico the "North American clean hydrogen market" including cooperation in R&D, safety codes and standards, cross-border hydrogen clusters, green freight corridors, and integrated maritime operations[46].

2.3.6 National: India's hydrogen strategy overview

The Indian Government has announced and is developing a National Green Hydrogen Mission, aiming to make India a global green hydrogen production and export hub as well as to take forward its decarbonisation plans to play a major role in the global clean energy transition initiatives. Plans are underway to enhance green hydrogen cooperation with Australia, France, Germany, Japan, UK and the US, while hydrogen will be a focus sector during India's G20 Presidency in 2023[47]. The Indian government has already notified the green hydrogen and green ammonia policy, according to which all statutory clearances will be provided in a time bound manner through a single portal and manufacturers will be provided land to set up storage bunkers near ports for export[48].

According to a recent report released by a government think-tank, the implied cumulative electrolyser capacity demand is expected to be 226 GW by 2050, by when the country's green hydrogen market is estimated to touch $340 billion and the electrolyser market would be worth $31 billion. The report has recommended that the country should develop green hydrogen standards and a labelling programme. Incidentally, around 43 countries already have green hydrogen strategies or roadmaps[49].

2.3.7 National: China's hydrogen strategy overview

China, which aims to reach carbon neutrality by 2060, has an annual hydrogen production that is reported to be 33 Mt, the largest in the world. China's first hydrogen powered industrial vehicle production line has been operationalised recently[50]. It has also been found that China-manufactured electrolysers are 75 percent cheaper than those made in the West[51]. The entire strategy is driven by its state-owned enterprises and through the establishment of regional

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44 https://www.democrats.senate.gov/imo/media/doc/inflation_reduction_act_one_page_summary.pdf. It contains the Innovative Clean Energy (Section 1703) and the Energy Infrastructure Reinvestment (EIR) Program.

45 GH2 (2022) "United States: Tax credits for green hydrogen under the US Inflation Reduction Act 2022" Green Hydrogen Organisation. August

46 Collins, Leigh (2023) "US, Canada and Mexico agree to develop 'North American clean hydrogen market'", www.hydrogeninsight.com (12.01.23)

47 Govt. of India, (2022a) "End Review 2022- Ministry of New and Renewable Energy". Ministry of New and Renewable Energy. Press Information Bureau. 20 December.

48 Govt. of India (2022b) "Ministry of Power notifies Green Hydrogen/ Green Ammonia Policy" Ministry of Power. Press Information Bureau. 17 Feb.

49 Raj, K. et al. (2022). Harnessing green hydrogen. Niti Aayog, RMI. June.

50 Jie, S. (2022) "China's first hydrogen industrial vehicle production line put into operation in the Greater Bay Area" Global Times. 4 Dec.

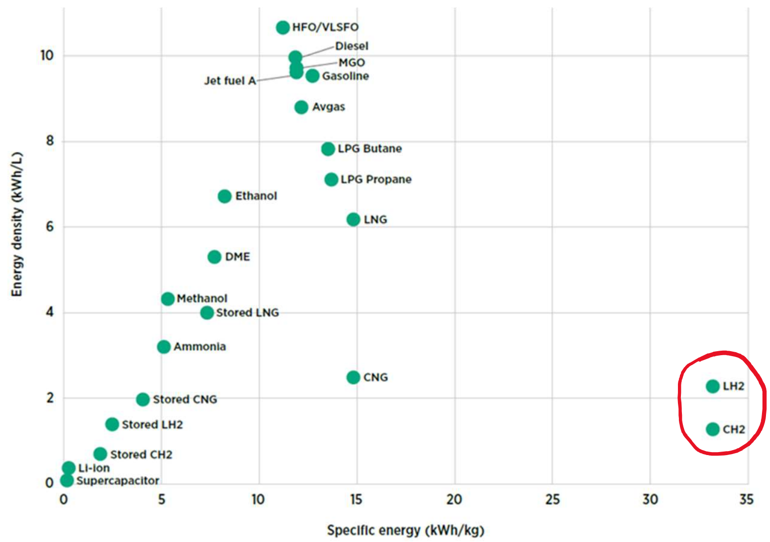
51 Van de Graaf, T. (2022) "Hydrogen's decade" IMF. December.

hydrogen clusters. The aim is to produce 200,000 tonnes of renewable hydrogen annually and 50,000 fuel cell vehicles by 2025[52].

2.4 Excursus: Hydrogen characteristics

2.4.1 Unique physical characteristics

The advantageous properties of hydrogen are (a) abundant, (b) non-toxic and ordorless, (c) production from water without direct emissions, (d) high energy conversion efficiencies, (e) different forms of storage available, (f) long distance transportation, (g) ease of conversion to other forms of energy, (h) higher heating values per kg then most conventional fossil fuels[53]. The downside is that in its gaseous form it requires high volumes. If it is transported in gaseous form only little weight and atomic mass can be shipped. From a transportation view this leads to a **H2 paradox** – despite its high energy per weight, the volume of a gaseous shipment requires to take weight and volume into consideration when designing efficient hydrogen supply chains. Also, additional energy will be needed for compression or liquefaction that cannot be completely recuperated later and thus leads to losses of useable energy.



Notes: Avgas = aviation gasoline; CH2 = hydrogen compressed at 70 MPa; CNG = natural gas compressed at 25 MPa; DME = dimethyl ether; HFO/VLSFO = heavy fuel oil/very low sulphur fuel oil; LH2 = liquefied hydrogen; Li-ion = lithium-ion battery; LNG = liquefied natural gas; LPG = liquefied petroleum gas; Stored CNG = Type IV tank at 250 bar; Stored CH2 = best available CH2 tanks at 70 MPa; Stored LH2 = current small-scale LH2 on-board tanks; Stored LNG = small-scale storage at cryogenic conditions; MGO = maritime gasoil. Numbers are expressed on a lower heating value (LHV) basis. Weight of the storage equipment is included.

Figure 8: Visualisation of the hydrogen paradox[54]

A phenomenon known in the air freight or parcel industry where the pricing is based on volumetric weight[55]. Compared to gasoline or diesel it is twice as energy efficient but requires four times more space for storage, which has implications on current traction vehicles and storage design.

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52 Gong, X. and Quitzow, R. (2022) "China's Emerging Hydrogen Economy: Policies, Institutions and Actors" 12 December

53 See Dincer/Acar (2015) "Review and evaluation of hydrogen production methods for better sustainability; Intern. Journal Hydrogen Energy and Wegner, Lindsey et al. (2021) Expected impacts on greenhouse gas and air pollutant emissions due to a possible transition towards a hydrogen economy in German road transport" Intern. Journal of Hydrogen Energy, 46, 5875-90

54 IRENA (2022) "Hydrogen Overview", https://www.irena.org/EnergyTransition/Technology/Hydrogen

55 Volumetric-weight (chargeable weight) is a mathematical computation of volume and weight parameters to form the basis for airfreight or parcel pricing.

When shipping or storing hydrogen in different forms of aggregation the amount of energy shipped or stored varies considerably and poses several challenges (see Figure 9).

H2 Compound	**Temperature** [°C]	**Density** [g/l]	**Volume =** Energy Density H2 [kWh/l]	**Weight =** Energy density (kWh/kg)	**Development status of transport**
H2 (1013 mbar)	25	0.08	0.003	33.3	
cH2 (500 bar)	0	33	1.1	33.3	
cH2 (640 bar)	-30	41.6	1.4	33.3	
cH2 (700 bar)	-30	43.9	1.5	33.3	
cH2 (1000 bar)	-30	55.8	1.9	33.3	
lH2	-253	71.0	2.4	33.3	TRL: 7
Ammonia (NH_3)	-33	674.0	3.6	5.2	TRL: 6-9
Methanol (CH_3OH)			5.1	6.49 /5.5	
Methane (CH_4)			5.9	13.9	

Figure 9: Overview of dimensions and energy of different hydrogen derivates[56]

Boil-off risk describes the unplanned emission of H2 during production, storage or transport that may lead to negative climate effects and potential explosion risk. In the risk assessment chapter 7 the paradox effects are balanced. It is worthwhile noting that the boil-off risk is dominantly reported only for the liquid transport form (cyryogenic)[57] and is less an issue for compressed hydrogen transport in containers[58] (see cH2 in Figure 9)

Through its ubiquitous useability in many applications and its potential as powerful energy storage, hydrogen has a unique potential to achieve the sector coupling of heat, energy and electric supply and material use thus promoting a carbon emission free world. Therefore, the carbon-free balancing between sectors can become easier to increase resilience of power supply combined with more localized and global production possibilities.

Another element that makes hydrogen different from other sources of fuel is that the geographical location of its production can be optimized in the value chain. It can either be produced where the renewable energies are generated (e.g. offshore wind parks) or where hydrogen is being consumed (e.g. industrial sites). This way the sum of distribution costs (e.g. for electricity grid and hydrogen pipeline network) and energy costs can be optimized.

The often-applied counterargument of the energy loss of hydrogen

1) Can be reduced if the whole business ecosystem is diligently designed

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[56] Sources: Marco Alvera (2021) The Hydrogen Revolution, p. 108; Gardiner, Monterey (2009), "Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs", DOE Hydrogen and Fuel Cells Program Record; Baetcke, Lars and Kaltschmitt, Martin (2018) "Hydrogen Storage for Mobile Application – Technologies and their Assessment"; https://www.engineeringtoolbox.com/ammonia-liquid-thermal-properties-d_1765.html; 39.4 kWh = higher heating value, 33.3 kWh = lower heating value

[57] Baetcke, Lars and Klatschmidtt, Martin (2018) "Hydrogen Storage for Mobile Application: Technologies and Their Assessment" in Azzaro-Pantel, Catherin (ed.) "Hydrogen Supply Chains – Design, Deployment and Operation ", Academic Press, p. 117f

[58] Robles, J.O. et al (2018) "Hydrogen Supply Chain Design – Key Technological Components and Sustainability Assessment", in Azzaro-Pantel, Catherin (ed.) "Hydrogen Supply Chains – Design, Deployment and Operation ", Academic Press, p. 61

2) Can be minimized through a systematic view of the production chain and optimal positioning within the energy system (e.g. use of electrolyzers' waste heat for district heating)
3) **Total costs** are the one and only relevant criterion, not theoretical physical efficiency green energy can be produced cheaply and that leads to competitive hydrogen cost.
4) **External effects** and costs of transport and conversion are fully transparently compared
5) Green energy can be produced cheaply and locally if minds and hearts are opened and regulatory/political barriers are lowered

2.4.2 Hydrogen's unique advantages and applications compared to fossil fuels for combined transport

The universal application of green hydrogen enables a carbon-free sector coupling approach (see Figure 10).

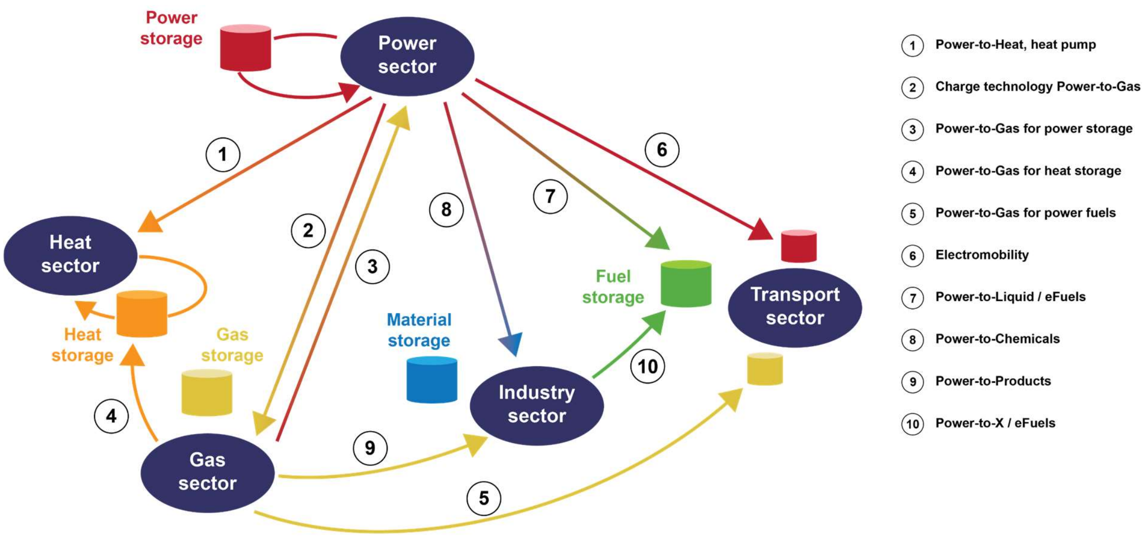


Figure 10: Sector coupling approach to increase long-term storage, resilience, and energy efficiency [59]

Hydrogen can replace natural gas to become the only at-scale technology for carbon-free sector coupling[60]. It can convert power into a usable form, store it and distribute it to end use sectors to meet their demand. Power-to-gas are the key elements in Figure 10 that can be substituted by hydrogen. Hydrogen has a threefold higher energy density per kg than natural gas and crude oil. It is an abundant resource on earth and the universe. Its density however poses a challenge.

Business ecosystem support is required to enable the sector coupling (see Figure 11).

[59] Based on Steiner, M and Specht, M (2021) "Power-to-Gas and Power-to-X: The history and results of developing the new storage concept"
[60] FCH (2019) "Hydrogen Roadmap Europe – A sustainable pathway for the European energy Transition"

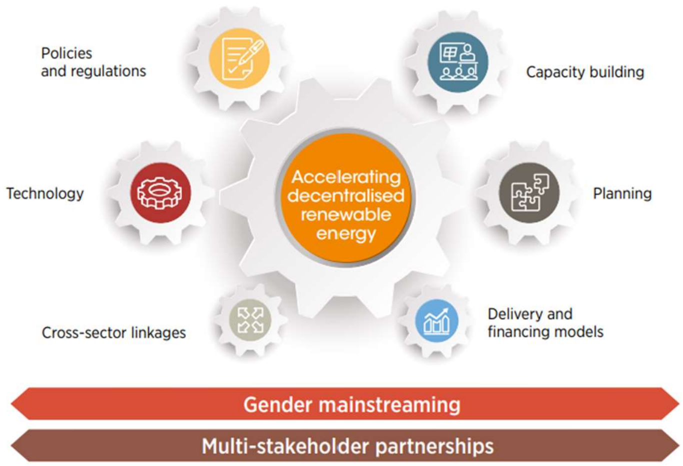


Figure 11: Generic requirements of sector coupling[61]

Hydrogen has a multi-purpose application potential but lacks widespread use:

1) Fuel all vehicle types and purposes
2) Store electricity
3) Apply for heating
4) Material use in petrochemical and chemical productions
5) Apply in steel and cement production processes
6) Metallurgical and ceramic production uses

One aspect should not be undervalued that hydrogen production is fully scalable from centralized large plants to small household or remote location production sites. Similarly, hydrogen distribution can me manifold – from large pipelines to small truck loads to meet the required local demand. For combined transport the flexibility, resilience and low carbon impact are advantages for medium sized demands to areas that are not close to ports or close to the hydrogen pipeline networks.

The supply of (green) hydrogen or hydrogen derivatives (e.g. Ammonia) can be performed via containers and the recipients can be many industries (see Figure 12). In times of shortages due to crisis or as a bridging solution in regions of incomplete hydrogen pipeline networks it can be re-integrated into the pipeline systems if the infrastructure is available. Another target can be to add to the future hydrogen storage systems (e.g. tanks or caverns) next to the direct use by industry or private consumption (mobility or heating). For ammonia industry feedstock, energy transport, and tank storage are the most likely use cases.

[61] IRENA (2022) World Energy Transitions Outlook 2022 1.5° C Pathway, p. 160

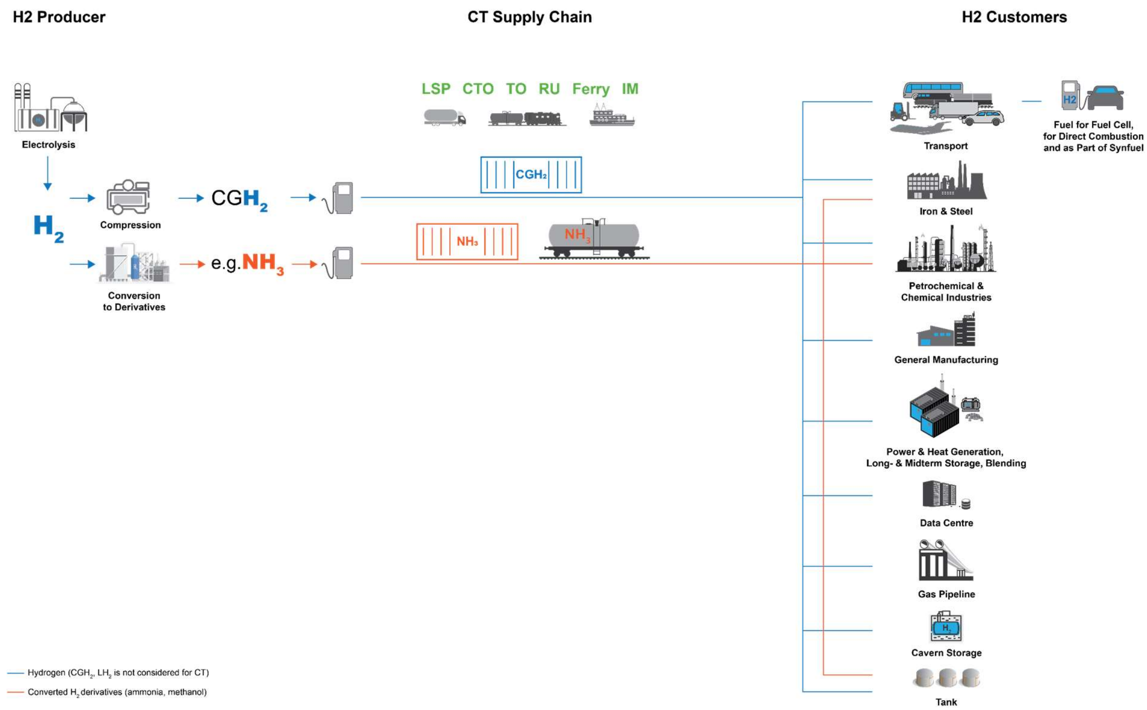


Figure 12: Road-rail CT's H_2 transport solution potential in Hydrogen Business Ecosystem

2.4.3 Past barriers can be overcome and offer historic opportunities for road-rail

The industrialisation of hydrogen technologies for rail transport equipment is suffering a chicken and egg problem. Due to the high cost of the container (> 3-4 times of a comparable ammonia or methane tank container) none of the 10 industry stakeholders interviewed have actively shipped hydrogen via rail yet or have heard of an example.

The current key drivers for the analysis of combined transport as complementary transport mode for shipping hydrogen via rail are:
(1) international trade restrictions due to geopolitical changes (esp. Russia-Ukraine war),
(2) uncertain increase of CO2 pricing,
(3) European gas supply crisis development,
(4) short supply of green hydrogen in Europe to be met via imports from low-cost international green hydrogen sources.

Combined transport offers one of the lowest CO2e impacts[62] of current transport modes and has proven to be a stable transportation option even under war situations (see Solidarity Lanes[63]). For the combined transport via the New Silk Roads there are different paths that can be used:

1) Northern corridor
2) Middle corridor

The Northern corridor is the faster and less costly alternative but if the Ukrainian-Russian war and the present sanctions against Russia may continue for five to ten years (most likely

[62] D-fine (2021) „A comparative study on CO_2 emissions in door-to-door combined transport"
[63] EC speech on success of Solidarity Lanes (08.12.22) https://ec.europa.eu/commission/presscorner/detail/en/SPEECH_22_7596

minimum until 2024) as military expert Pierre Servant stated[64], then the further expansion and service quality improvement on the middle corridor are even more required.

The **historic opportunity** is to use green power and convert it locally to green hydrogen or its derivates while having a network of pipelines and rail transport options for inland distribution of hydrogen or intercontinental transport to deliver it cost-efficiently to more remote consumers.

The possible **virtuous cycle** that could make the strong increase of hydrogen production and transportation offerings possible can materialize if sufficiently nurtured (see Figure 13). The prerequisites are the supply of hydrogen and the industrialisation of the production of it to increase the conversion potential and thereby higher customer demand which increases again the incentives to ramp-up supply of hydrogen.

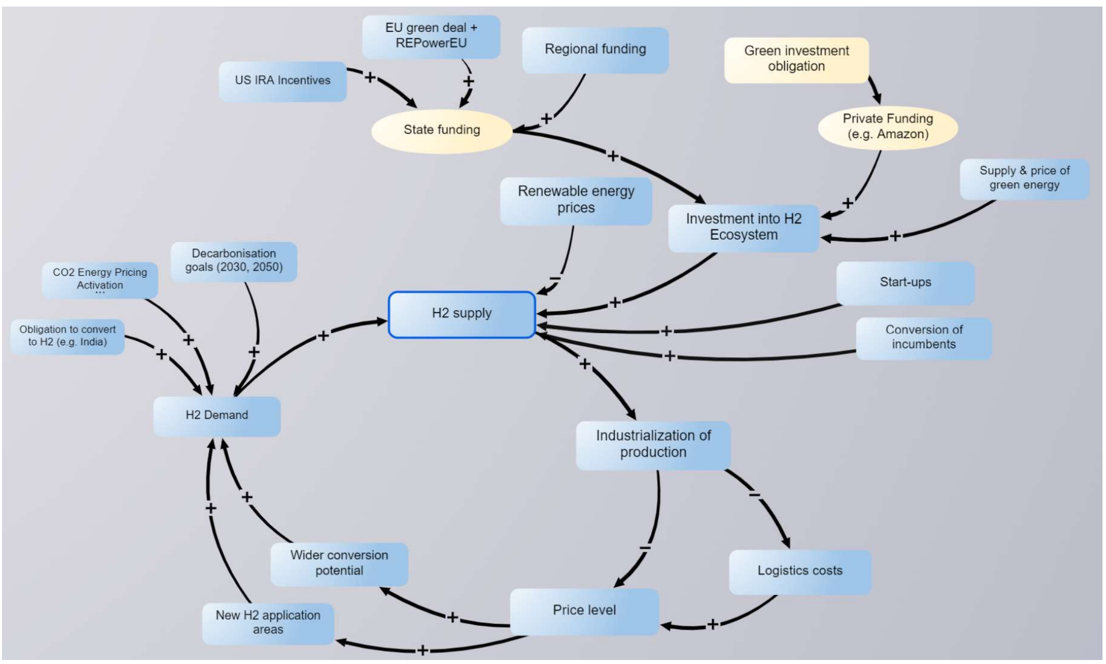


Figure 13: H2 supply and demand model (own research)[65]

2.5 Path towards hydrogen as a reliable, green and cost-efficient source for energy, heat and feedstock via combined transport

Co-existence and funding of both battery-based and hydrogen-based power, heat and feedstock supply and storage are required as highlighted by IRENA (see Figure 14).

[64] Britta Sandberg interviewed Pierre Servant (Spiegel, 09.12.2022) "Wir erleben gerade den Beginn einer anderen Welt"

[65] Legend: "+" depicts a strengthening impact ("the more the more"), "-" depicts an dampening impact ("the more the less")

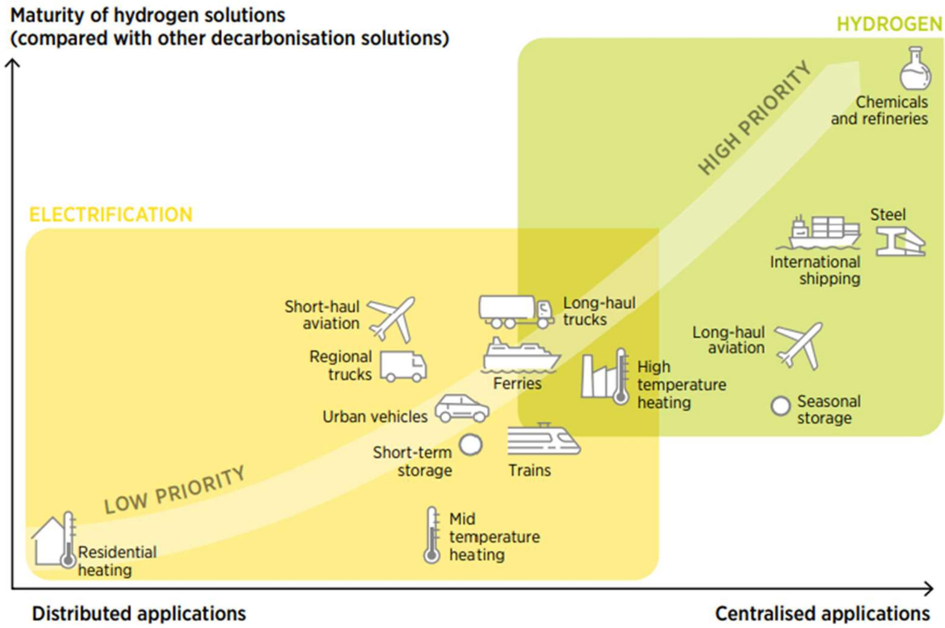


Figure 14: High priority and grey areas for the application of hydrogen as energy or feedstock source [66]

Long-haul trucks and trains are to be electrified or operated with hydrogen on a case-by-case basis depending on the ease of providing the electric or hydrogen infrastructure and the demand patterns. The supply of hydrogen for the logistics industry can be much more decentralized than the categorisation of IRENA indicates if SMEs and regional depots of logistics service providers are included.

[66] IRENA (2022) World Energy Transitions Outlook 2022 1.5° C Pathway: p. 277 - not all application areas are visualised

Key take aways:

1) Hydrogen as good offers opportunity for more carbon-reduced business for combined transport that is underexplored so far. We aim to close this gap.
2) This new opportunity needs to be detailed and its success potential to be explored in the context of the full Hydrogen Business Ecosystem transformation to avoid wrong timing or under or over capacities.
3) Hydrogen as energy source for propulsion should not be neglected for other transport modes but also for rail to decarbonise the remaining not electrified lines or shunting yards it is a small but not insignificant task (see Figure 15~~Figure 15~~).

Hydrogen is seen as primary or secondary source of energy for transport in the future and this justifies its analysis to prepare combined transport for the likely future changes.

Green Propulsion Energy Source Alternatives

	1rst	2nd	3rd	Consumption EU [GWh]
Aircraft	Hydrogen	Synfuel		0.7
Ship	Ammonia	Hydrogen		0.6
Road	Battery	Hydrogen	Synfuel	3.6
Rail	Electricity	Hydrogen	Battery	0.1

Figure 15: Propulsion alternatives[67]

The primary focus is this pre-study is the transport of green hydrogen as a widely applicable source of energy or feedstock to decarbonise most of the industries and private households.

[67] Source: https://www.eea.europa.eu/data-and-maps/indicators/transport-final-energy-consumption-by-mode/assessment-10

3 Business needs roughly delineated

3.1 Demand and supply scenario selection

Since the purpose of the study is to explore the future requirements of combined transport in the hydrogen business ecosystem the choice was made to focus on the active carbon reduction scenarios. The little to no change scenario ("pessimistic") is neither from future climate conditions desirable nor currently actively pursued by the G20 governments. The pessimistic scenario must be avoided to sustain a suitable climate on earth and avoid the negative effects of economic downturn and costs of damages due to climate change[68]. Therefore, we focus on the currently still emerging but more likely progressive (2°C global warming) and ambitions (closer to 1.5°C) global warming scenarios. This choice is relevant as it has implications on the chosen research forecasts and models.

	Key Assumptions / Scenario	Pessimistic (2.5°C to 3°C only)	Progressive (2 °C warming)	Ambitious (closer to 1.5°C)
Regulatory	EU H2 targets reached	☒ 20% under achievement	☑	☑ 10% over achievement (national + EU programs)
Technology	Progress 2030 [%] (Innovation + Capacity)	10%	20%	30%
Market	H2 demand development	Low H2 penetration in road, rail and CT and other sectors (10%)	Medium H2 penetration in road, rail and CT and other sectors (20%)	High H2 penetration in road, rail and CT and other sectors (30%)
Climate	Tipping Points Cascade	☒	☑ partially	☑

Figure 16: Choice of scenarios

In the progressive scenario the minimum Paris agreement goals will be achieved and we assume a considerable innovation progress and a moderate penetration of hydrogen as propulsion technology for transport. On the climate assumptions tipping points are partially thinkable and can be compensated.

In the ambitions scenario the regulatory push is increased, private investment and the national efforts are overachieved. This is complemented by more investment into R&D and a 30% progress rate due to global competition. In this case prices can drop to a level where a higher adoption in the landbound transport is feasible. The most extreme scenarios of 100% green powered and no emission scenario on a global basis are not considered as realistic but a 95% reduction of CO2 emission compared to 1990 until 2050 is an ambitious, but possible goal[69].

[68] Deloitte Economic Institute (2021) "Germany's turning point - Accelerating new growth on the path to net zero" estimates an average annual 0.6% shrinking economy, 470k more unemployed and 730 billion loss of gross domestic product if temperature increase by 3 degrees.

[69] E.g. Dutch climate policy targets https://www.government.nl/topics/climate-change/climate-policy ; EU's target is even more ambitious aiming for net zero GHG emissions until 2050 (see Regulation (EU) 2021/1119 ("European Climate Law")

3.1.1 Global Hydrogen Demand and Supply Pattern Context

The core assumption of the demand patterns is that Europe will require a considerable number of sources to reach its targets to import 10 mio tonnes of hydrogen or 1200 PJ. Europe plans to make hydrogen a central part of its energy strategy. The share of hydrogen in Europe's energy mix is projected to grow from the current less than 2% to 13-14% by 2050[70]. Our initial analysis suggests that the flows depicted below are not complete. Central Asia is not depicted as a key hydrogen source and the planned amounts will only be delivered From the Middle East and South Africa.

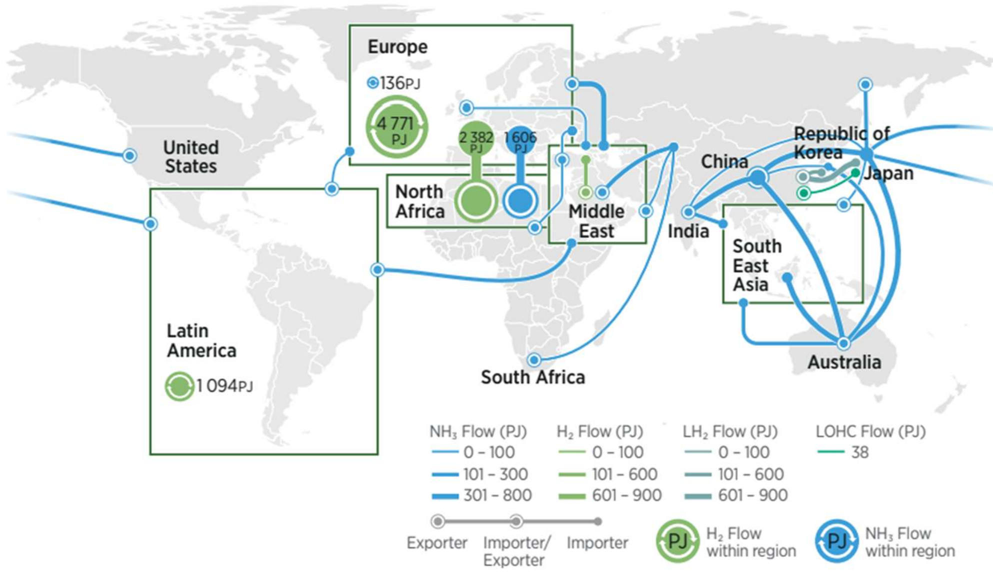


Figure 17: Global supply and demand forecast for 2030 (IRENA)[71]

3.1.2 Global demand break-down

The global demand for hydrogen is based on several assumptions and various reports show a double-digit variance depending on the assumed use of hydrogen and its derivatives. Figure 18 shows an average forecast of several recent reports focussing on the green hydrogen.

[70] European Commission "COM(2020) 301 final - A hydrogen strategy for a climate-neutral Europe", (08.07.2020). The figures only cover the energy use of hydrogen.

[71] IRENA (2022) GLOBAL HYDROGEN TRADE TO MEET THE 1.5°C CLIMATE GOAL – Part1, p. 20

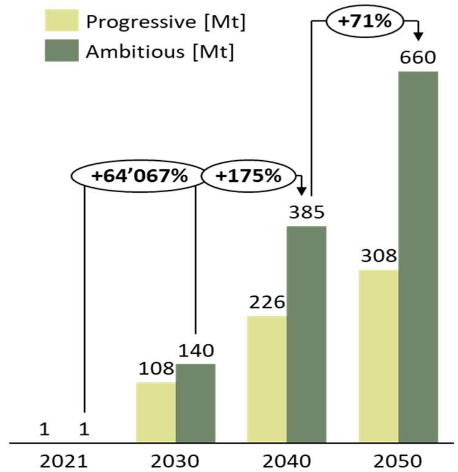
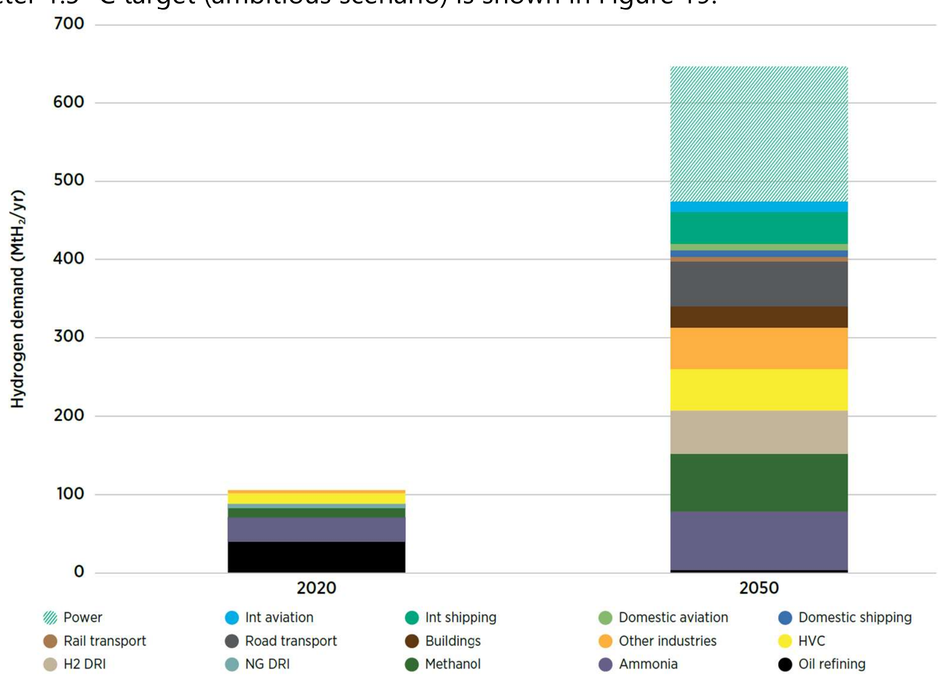


Figure 18: Global demand growth forecast for green hydrogen[72]

Global hydrogen demand forecast broken down to its most likely consuming sectors to meet the stricter 1.5 °C target (ambitious scenario) is shown in Figure 19:



Note: Hydrogen demand for 2020 excludes hydrogen as part of the mix of off-gases for steel production. DRI = direct reduced iron; HVC = high-value chemicals; Int = international; NG = natural gas.

Figure 19: IRENA global hydrogen demand estimation without seasonal storage volumes (2022)[73]

On a global scale the number of applications of hydrogen need to rise considerably and their share rises to a total demand increase by about 500% in 30 years or a CAGR of about 6% p.a.[74].

[72] The growth from 2021 to 2030 is less steep if the existing hydrogen sources are integrated. Since grey or black hydrogen will need to be converted or capturing extended the change of the production remains as extreme as indicated but not until 2030. Sources are several meta-studies (e.g. WorldEnergyForum (2022), Hydrogen Council (690Mt), IAE (450 Mt), IRENA (2022a) (614 Mt), JRC (2022) etc.). In case of ramp-up delays partial compensation with blue hydrogen can be a back-up solution.

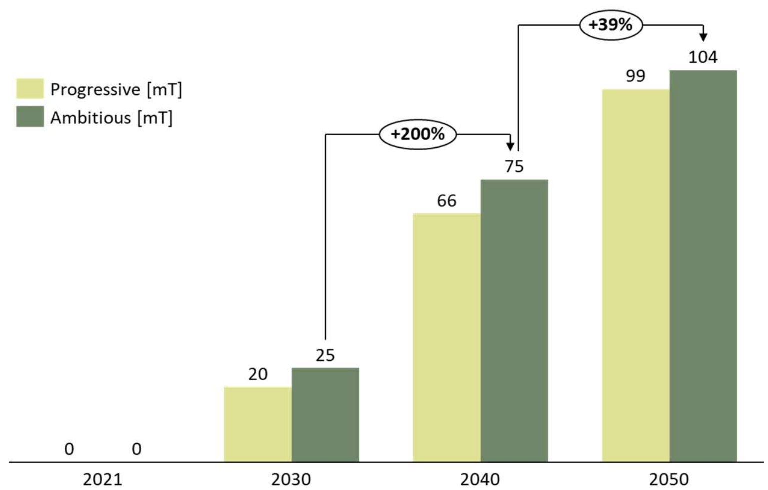
[73] IRENA (2022) "Global Hydrogen Trade to Meet the 1.5 Climate Goal, Part 1: Trade Outlook for 2050 and way forward" p. 32

[74] The only exception is the use of hydrogen in the petroleum industry if the forecasted substitution will materialize.

These figures are multiplied by a factor 4 (CAGR 25%) if the increase of a 100% green hydrogen by 2050 is targeted. Even more growth is required if (green) hydrogen is used to substitute natural gas as seasonal storage power buffer stock in countries like Germany that need to balance their lower green energy supply in the winter[75]. These growth figures corroborate our underlying claim that building the hydrogen business and public ecosystem is a major global collaborative effort to avoid catastrophic climate changes. A historic analogy is the successful implementation of the CFC and HFC initiatives of the Montreal Protocol 1987 to avoid the growth of the ozone hole. The difference is that it effects a wider range of businesses and tangible real-world actions need to start now.

3.2 Customer demand for hydrogen

The demand estimation is 10 Mt H_2 to be imported to EU[76] and 10 Mt to be produced within EU by 2030. The demand forecast for Europe of more than 100 Mt by 2050 requires a deep integration of H_2 not only into existing industries but into almost all areas of economic activity. The most ambitious scenarios assume that up to 24 % of the European energy demand will be fulfilled by hydrogen and its derivatives[77].



Sources: Hydrogen Council (2022) "Global Hydrogen Flows: Hydrogen trade as a key enable for efficient decarbonization", October 2022; Villavicencio, Manuel (2021) "Hydrogen for Europe study", Deloitte France for IOGP EU

Figure 20: Forecasted EU development of green hydrogen demand until 2050 (top-down calculation) [78]

The top-down target figures shown in Figure 20 need to be broken down into the different sectors before the sources can be allocated. The challenge of existing demand forecast reports is their strong variance in scope as many meta studies[79] show. Not only different assumptions on the penetration level of H_2 by sector but additionally one or more hydrogen relevant

[75] This effect is not fully reflected in the IRENA report yet, but planned for the future

[76] "Fit for 55" (25.04.23) https://www.consilium.europa.eu/en/press/press-releases/2023/04/25/fit-for-55-council-adopts-key-pieces-of-legislation-delivering-on-2030-climate-targets/
RePowerEU (18.05.2022) ttps://ec.europa.eu/commission/presscorner/detail/en/ip_22_3131

[77] Hydrogen Europe (2019) "Hydrogen Roadmap Europe – A Sustainable Pathway for the European Energy Transition", Fuel Cells and Hydrogen 2 Joint Undertaking

[78] The conversion potential of existing H_2 demand is not shown as the current supply of green H_2 is not reliably available

[79] Wagemann, Kurt (2022) „"Zwischenergebnisse der Meta-Analyse", Wietschel, M. et al (2021) Metastudie Wasserstoff-Auswertung von Energiesystemstudien, Fraunhofer, Riemer, Matia (2022) Future hydrogen demand – A cross-ectoral, global meta-analysis", Fraunhofer, WorldEnergyCouncil (2021) „Hydrogen on the Horizon: Ready, Almost Set, Go?

industry segments are omitted. Current grey or black hydrogen production in Europe is estimated at 8 Mt in 2022[80] which is not considered will be part of the future conversion needs. The break-down of the ambitious and the progressive hydrogen demand from a bottom-up calculation are the following:

Progressive: **Ambitious:**

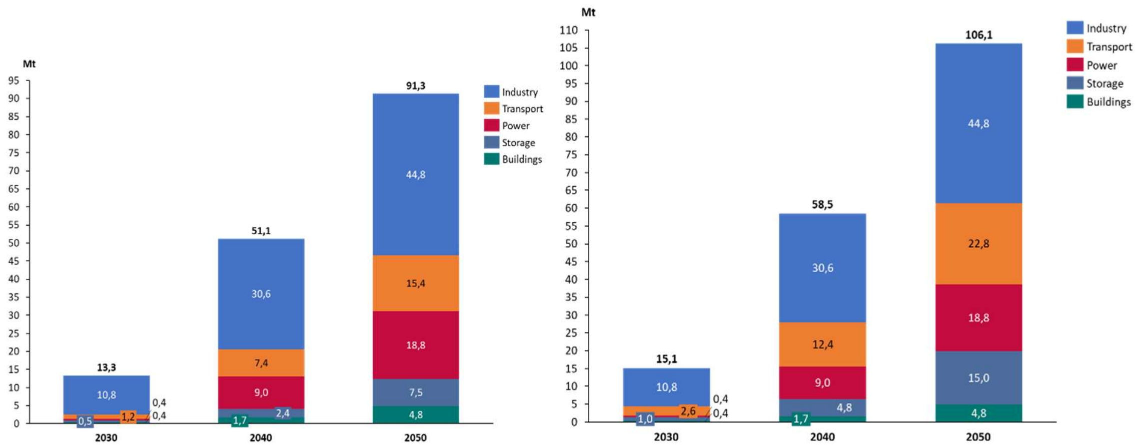


Figure 21: Progressive and Ambitious sector break-down (bottom-up)[81]

3.2.1 Practical Case: BASF Green H2 supply, demand and shipping perspective

BASF as the world's biggest chemical company invests into the production of green hydrogen with the support of EU funding of 134 mio € [82] at their site in Schwarzheide (Germany). This is one amongst several other projects to decarbonize their production and continuously reduce their CO2 footprint in the supply chain[83]. BASF is also a consumer of hydrogen as well as an important customer for rail within the EU.

Next to the customer and producer perspective BASF invests into the development of optimised tank containers called BTCs. BTCs are in use for liquids and some liquefied gases, however BTCs could in the future due to their high volumes be a promising path as up to 5 tons of hydrogen payload are possible for liquid hydrogen. Their concept uses (isolated) steel tanks compared to more expensive and less robust composite approaches.

BASF is actively shaping the container design to optimise the payload and the filling processes. The BTC containers are steel based due to the lifetime, price and temperature insensitivity. An overview of container types summarises the potential compared to standard approx. 40 m^3 containers (see Figure 22~~Figure 22~~).

[80] Aurora Energy Research (2022) "EU Hydrogen Market Attractiveness Report (HyMAR), October

[81] Own collection of data sources and assumptions

[82] https://www.reuters.com/business/energy/eu-approves-german-measure-support-basf-production-renewable-hydrogen-2022-10-03/

[83] https://www.basf.com/global/en/who-we-are/organization/group-companies/BASF_Renewable-Energy-GmbH/projects.html

Dimension- Type	Pressure [bar]	Volume [m3]
BTC – 40ft – orange	L10DH	43
BTC – 45ft – orange	L10DH	63
BTC – 45ft - light blue	L10BH	63
BTC – 45ft – red (rubber coating)	L4DH	62
BTC - 45ft – dark blue	L4BH	63
BTC - 45ft - dark green	L4BH	53
BTC - 52ft - light green	L4BH	73
BTC – 52ft – white-orange for gases	22	83

Figure 22: BASF BTC container types used for liquids and liquified gases

BASF is in the process of patenting an optimised loading and unloading process. The need to standardise the future container infrastructure and handling processes globally is shared with UIRR's interest to foster interoperability to avoid high investment expenditure that can otherwise only be used in point-to-point connections.

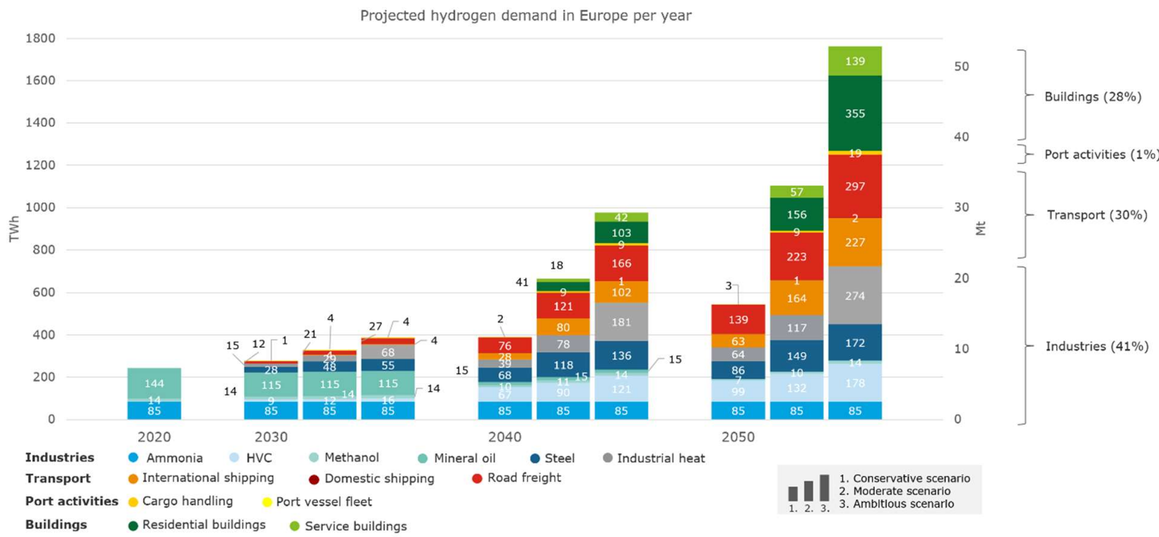
Currently BASF is not using BTCs to transport hydrogen as the internal projects are defined to consume the hydrogen at the sites. Current hydrogen needs are fulfilled in a compound production process not requiring external supply. In addition, filling stations (gas station) are planned for hydrogen powered trucks which could be a future potential to be explored.

Unfortunately, the potential producers of BTC tank containers did not provide input in meaningful time so that there is no cost estimation available for the BTC design for a specific business case calculation. With the assumption that costs for steel tanks are lower and the capacity is higher due to more volume compared to multiple tubes the business case should be analysed in detail once the facts are available.

3.2.2 Break-down of EU Hydrogen energy and feedstock supply

The forecast of the future transition to hydrogen on an EU basis can only be done with a set of assumptions and a selection of scope. Many studies on the demand of hydrogen exist but of the 20 studies analysed most have shown deficits in terms of selection of hydrogen sources and the inclusion of rail as consumer of hydrogen.

The many meta studies or specific studies such as the Deloitte study from 2022 (see Figure 23) indicate a split into broad customer groups but miss assumptions on seasonal storage and rail transport as additional transport mode at all.



ote: The large differences in estimates of future hydrogen demand reflect the great degree of uncertainty that currently exists in the adoption of hydrogen as a replacement for fossil fuels in some sectors, notably the 'Buildings' sectors (heating of sidential and service buildings). For all the other sectors in scope of this study (industries, transport and port activities), all three scenarios foresee a role for hydrogen, at least to some extent.

Figure 23: Hydrogen consumers in Europe (Deloitte selection of hydrogen uses) [84]

Since the future demand estimation is a relevant element to identify a suitable supply chain the following chapters will detail a selection of different demand forecast studies and own forecasts to compile a more complete picture for Europe and in particular for the focus country Germany.

3.2.3 Hydrogen and derivatives as feedstock

Green hydrogen has an ample use as feedstock in the petro-chemical industry, iron and steel, industrial process heat, and hydrogen derivatives (e.g. ammonia for fertilisers or methanol). The 9.7 Mt of hydrogen (2021) currently produced within Europe are largely not green hydrogen[85].

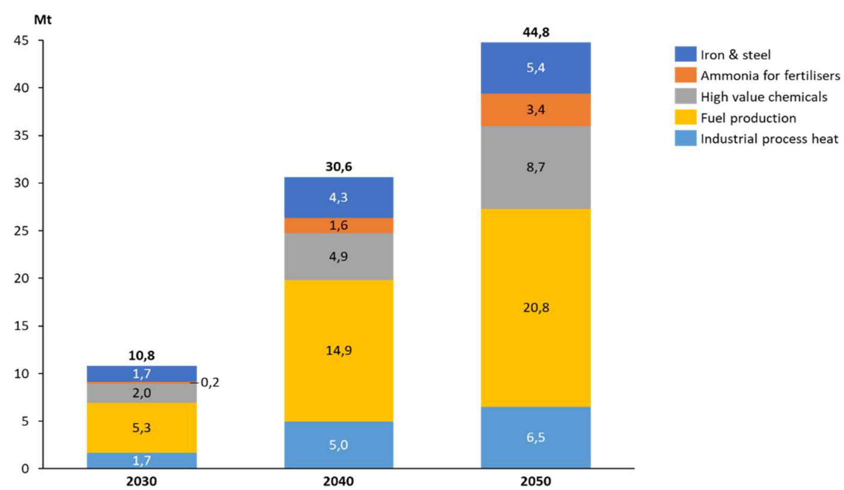


Figure 24: Estimated volume development (ambitious scenario)

[84] Deloitte (2022) "Study on hydrogen in ports and industrial coastal areas", TRA Lisbon, 15.11.2022 omitting rail freight as consumer of hydrogen and hydrogen power supply

[85] Kaoulaki, G et al. (2021) "Green hydrogen in Europe – A regional assessment – Substituting existing production with electrolysis powered by renewables", Energy Conversion and Management (228)

3.2.4 Hydrogen as source for power generation and short-term storage

Hydrogen can be used to produce power as back-up solution or for remote locations without access to the grid for energy generation. Currently on a global level only 0.2% of power generation use hydrogen (mainly in Asia) [86]. The estimated demand on EU level is still vague for the power sector except for Portugal. For the period from 2030-2050 only Japan, Korea and Australia are planning a large use of hydrogen or ammonia for storage of up to 20 Mt by 2040. Our estimation for the EU is based for this sector and is below the sum of Japan, Korea and Australia[87].

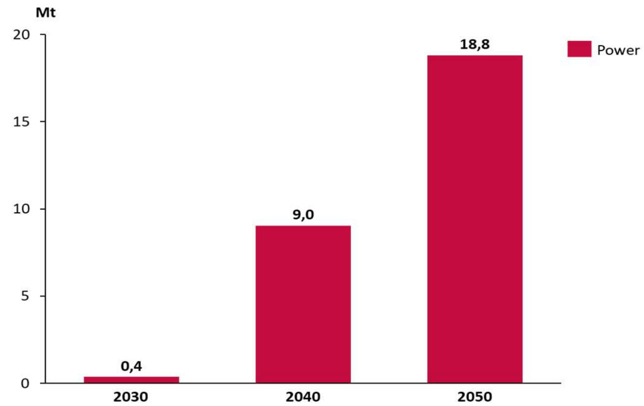


Figure 25: Hydrogen demand forecast from the power sector (ambitious scenario)

3.2.5 Hydrogen for heating

The building sector will undergo strong transformation due to the planned ETS(4) pricing in 2025[88]. Especially the energy consumption for heating is an area where a large proportion of GHG emissions can be avoided. Using hydrogen for heating is a useful application in case of no access to the electricity grid, high local electricity prices or if a building or area has more green energy supply than average demand. In these cases, local industrial compounds, district heating or even household heating solutions are thinkable. One example is the PICEA[89] solution for self-sustaining households. In current regulations the adoption is likely to be not high (less than 1%), but it may change if there is a revision of current regulation due to other insights and sector coupling needs.

If heating source decisions are not only based on the efficiency of heat pumps[90] but are taking wider energy coupling options and other local factors into account local and district heating options using hydrogen can be beneficial if waste heat from hydrogen production, seasonal storage or other sources can be used[91]. The contribution towards decarbonisation of the heat sector can be considered as relevant alternative to complement the solution scope. The

[86] IEA (2022) "Global Hydrogen Review 2022"

[87] Guidehouse (2021): "European Hydrogen Backbone - Analysing future demand, supply, and transport of hydrogen"

[88] https://www.europarl.europa.eu/legislative-train/package-fit-for-55/file-revision-of-the-eu-emission-trading-system-(ets)

[89] Self-sufficient household solar and hydrogen based seasonal power supply solution example (e.g. PICEA from HPS https://www.homepowersolutions.de/en/)

[90] Gudmundsson, O and Thorsen J.E. (2022) "Source-to-sink efficiency of blue and green district heating and hydrogen-based heat supply systems", Smart Energy (6)

[91] Böhm, Hans et al. (2021) "Power-to-hydrogen & district heating: Technology-based and infrastructure-oriented analysis of (future) sector coupling potentials", Int. J. Hydrogen Energy (46) 4

Hy4Heat project in the U.K. started in 2017 and has shown that the application of hydrogen for household heating is feasible. It will be extended to 300 households in the project H100[92]. For Germany a recent Fraunhofer study elaborated a high potential for district heating if the hydrogen prices are on the lower end of the 2.7-3.8 EUR range in 2030[93].

3.2.6 Hydrogen demand for seasonal storage

Hydrogen can be used for the carbon-free sector coupling and especially seasonal storage to cover the energy demand that is expensive to fulfil via other means (e.g. batteries or pump-storage). Current caverns for natural gas can be used to store large amounts of hydrogen with little adaptation needs. Several projects in Europe are in planning in France and Germany. If there is no wind or solar power, then especially in winter hydrogen must be stored and burned[94]. Contributing to an increased amount of seasonal energy storage is the fact that not only solar production decreases but electric cars require more energy in winter (approx. 15-20%).

The centralised seasonal power storage of hydrogen (e.g. in caverns or retro-fitted gas storage) has the largest potential in Germany with (61 TWh) followed by Italy (47 TWh) and the Netherlands (35 TWh) but there are no specific plans yet[95]. The three countries sum-up to 4.2 Mt hydrogen as maximum storage potential. Complementary, more decentralised applications can be medium scale and small scale (e.g. PICEA even on household level[96]). The current EU regulation may increases the hurdle for localized energy production and storage[97] which could lower the growth in this area.

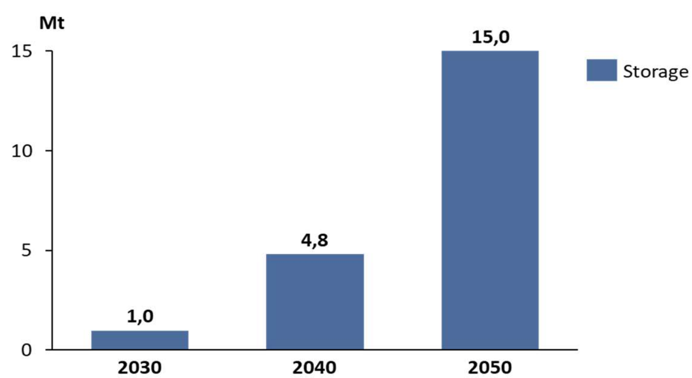


Figure 26: Seasonal storage demand forecast (ambitious scenario)

3.2.7 Hydrogen for transportation and mobility

[92] Department for Energy Security & Net Zero (2023) "Evaluation of Hy4Heat – Final Report"; https://www.h100fife.co.uk/

[93] Thomsen, Jessica and Lenz, Matthias (2022) "Bottom-Up Studie zu Pfadoptionen einer effizienten und sozialverträglichen Dekarbonisierung des Wärmesektors", Fraunhofer. The analysis of the changes of the existing network were not explored.

[94] Wambach, Achim (2022) "Klima muss sich lohnen", Herder

[95] https://www.statista.com/statistics/1267919/potential-hydrogen-storage-capacity-in-europe-by-country/

[96] Self-sufficient household solar and hydrogen based seasonal power supply solutions exist (e.g. PICEA from HPS https://www.homepowersolutions.de/en/)

[97] Delegated Regulation C(2023) 1087 final "establishing a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels on non-biological origin", 10.02.2023

Several transport sector specific initiatives are started to support the decarbonization (e.g. ReFuelEU Aviation, Fuel EU Maritime, or Alternative Fuel Infrastructure Regulation). The transport sector is slow to adapt to the Fit-for-55 and other EU greening initiatives and lags behind (see ch. 2.2). The percentage of green energy used even declined from 10.3% in 2020 to 9.1% in 2021 (13% down)[98]. One lever to change this is the extension of the European Emissions Trading System (EU ETS II) to the maritime and commercial road-based transport systems by 2025[99]. Private transport to be included in 2029.

3.2.7.1 Hydrogen to power road transport

Hydrogen demand in transport to meet emission reduction is rarely calculated. However, a rough-cut simulation will lead to a significant amount on the assumption of a 30:70 split of total truck shipments and a 50:50 split for long-haul shipments by 2045 due to the elimination of the sale of ICE heavy trucks.

Several reports focus on the application of hydrogen on the hard-to-abate or the hard-to-electrify transport needs and limit it to maritime and aviation[100]. This neglects applications where electricity is not available or expensive to deliver (e.g. remote areas) or where there is an operational trade-off between battery deficits (loading-time, resource scarcity, weight) versus hydrogen in many transport segments where local production is feasible and extra demand may be supplied via external hydrogen supply. Examples are forklift fleets for logistics centres, heavy and long-distance transports. Additionally, several car manufacturers extend their hydrogen offerings to be not only dependent on the electronic propulsion technology.

On-top of the above-mentioned arguments the dichotomization is not correct as there are combinations of location, energy price, heat, and application type where either electric propulsion or hydrogen is more beneficial and both are available and tested.

For a transparent and fair evaluation, the negative impact of battery weight is often ignored not shown in the chosen KPIs. Well-to-wheel efficiency calculations ignore the vehicle weight, the energy and convenience losses as well as availability deficits due to long charging times. The spectrum of hydrogen as source for propulsion on road is multifold. Depending on the usage profile, time for filling process, power need and tour profile the logistics industry applications reach from heavy trucks, reach stackers, forklifts to sprinters and also passenger cars. Some estimates reach more than 6 Mt hydrogen for road transport alone by 2035 in Europe (see Figure 27).

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[98] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics, accessed 05.04.2023

[99] https://www.europarl.europa.eu/legislative-train/package-fit-for-55/file-revision-of-the-eu-emission-trading-system-(ets)

[100] Rainer Quitzow et al (2023) "Building partnerships for an international hydrogen economy – Entry-points for European policy action", FES diskurs; Mc Kinnon, Alan (2022) "Innovative Concepts and Services for Zero-emission Mobility of People and Logistics", TRA Lisbon, 15.11.2022

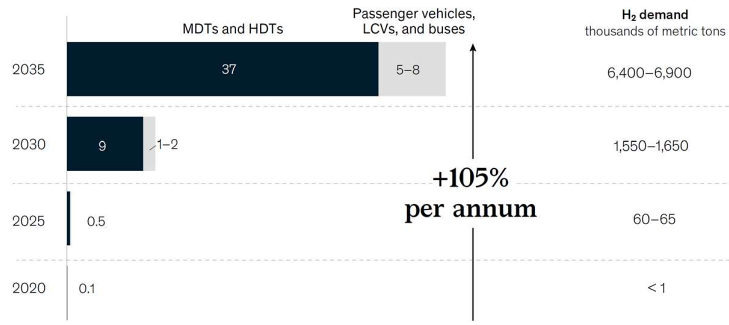

Figure 27: Estimation of the H_2 road refuelling demand ramp-up in EU [billion EUR] [101]

With the Alternative Fuels Infrastructure Regulation (AFIR) initiative the minimum infrastructure for multimodal gaseous hydrogen (according to ISO/TS 20100 at 700 bar[102]) and electric filling stations will be established for road, rail air and ships. Starting in 2026 by 2030 each 200 km on the TEN-T network and in all urban nodes one hydrogen fuelling station will be established to deliver up to 1 ton of hydrogen per day. However, the supply of hydrogen of about 1 ton per day seems to be underexplored[103]. Industry associations want to increase the density of the fuelling station network and supply to overcome the chicken-and-egg barrier. The starting maximum demand will be 123k tons of hydrogen supply in 2030 for road focused filling stations[104].

An incomplete list of current activities:

- Transport via hydrogen on water (e.g. startups like unleash-future-boats)
- Private cars existing product lines and recent pilots announcements (BMW, Hyundai, Toyota with two cars[105])
- Hydrogen to power trucks in Switzerland to run 5 million km (Hyundai road fleet[106])

The economic impact will change with ETS (II) in operation by 2025[107]. By then road transport will be included into the CO_2 certificate trade.

3.2.7.2 Hydrogen demand to fuel railway systems

The demand for hydrogen powered freight and passenger trains depends on the regional coverage of electricity powered rail systems. This varies by country considerably. The average is at 56.65% with countries close to 100% (Switzerland) and the Republic of Ireland at 2.8% [108].

[101] Applications for special logistics vehicles (e.g. forklifts, reach stackers) not included in report by Bernd Heid et al. (2023) "Unlocking hydrogen's power for long-haul freight transport", McKinsey

[102] COM(2021) 559 final "REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU of the European Parliament and of the Council (14.07.2021)

[103] No plausible response to this question in an ALICE presentation on hydrogen filling stations in March 2023

[104] Based on 49'700 km Core TEN-T road network 2030 European Court of Auditors (2020) "The EU core road network: shorter travel times but network not yet fully functional" plus 88 urban centres in 2020. Their number is likely to rise > 400 after redefining & reflecting the EU expansion since 2013 (https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_6725).

[105] Toyota announced to bring next to the Mirai also Toyota Crown in autumn 2023, BMW announced early 2023

[106] https://www.hyundaimotorgroup.com/news/CONT0000000000061412

[107] https://www.europarl.europa.eu/legislative-train/package-fit-for-55/file-revision-of-the-eu-emission-trading-system-(ets)

[108] Statista (2022) "Percentage of the railway lines in use in Europe in 2020 which were electrified, by country", https://www.statista.com/statistics/451522/share-of-the-rail-network-which-is-electrified-in-europe/ (18.02.23)

In the cargo rail freight part shunting locomotives are often diesel based and only gradually substituted by electrified or hydrogen-based locomotives. The estimated amount of hydrogen-based locomotives by 2030 is about 20% of all locomotives and about 950 locomotives in the base scenario and 1750 in the high scenario[109]. With an average consumption of 0.9 kg and 600 km the total demand will start between 0.2 Mt to 0.3 Mt hydrogen.

Based on previous work we forecast the following hydrogen need to supply the remaining non-electrified railway tracks within Europe (see Figure 28).

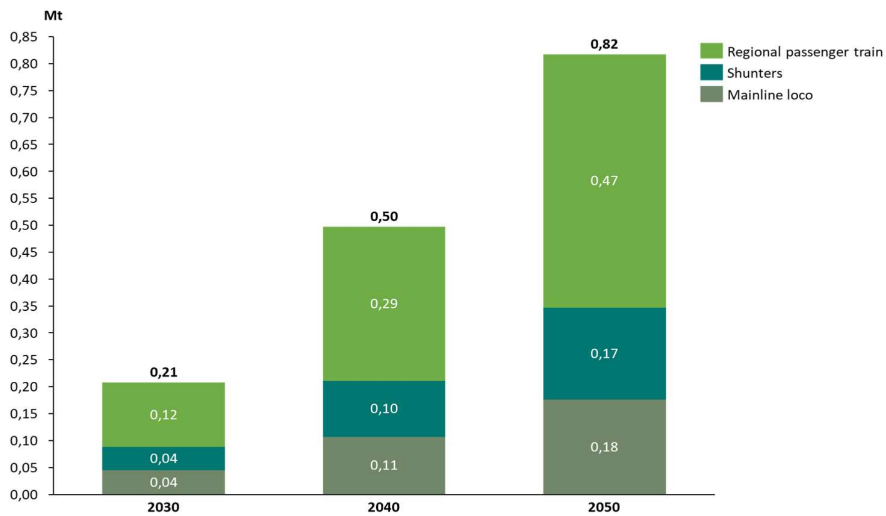

Figure 28: Railway hydrogen demand forecast (ambitious scenario)

Although it may seem little demand the volume is an equivalent of about 1’700-3’300 compressed hydrogen trains in 2030 and about 6’000-8’000 in 2040 depending on the scenario that materialises.

The calculation of the hydrogen demand in the rail sector is based on the Eurostat 2020 figures on diesel and electrified assets, i.e. locomotives and railcars and the assumption that the rail sector will experience a growth rate of five percent per decade (based on Unife 2023). In addition, the projections of two scenarios on the number of hydrogen-powered trains and locomotives for 2030 from the Shift-2-Rail Report 1 are taken into consideration to calculate the potential demand of hydrogen in the rail sector.

3.2.7.3 Hydrogen for air transport

Aviation is one of the hard to abate areas where early reports from 2021 assume only a low demand for hydrogen. Air traffic consumes roughly 1670 PJ (2021 incl. UK)[110] which is equivalent to a total 14.6 Mt/a hydrogen (100% conversion).

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[109] Shift-2-Rail (2019) “Study on the use of fuel cells & hydrogen in the railway environment – Report 1: State of the art & business case and market potential”

[110] See https://knoema.com/data/consumption+jet-fuel+europe

Due to the energy intensity required for long haul flights only expensive synfuel (synthetic kerosene) are a current long-term solution[111]. However, Airbus recently announced that they want to explore liquid hydrogen for medium distance (< 2000 km) and passenger sizes (< 200) liquid hydrogen in operation by 2035[112]. If this measure is successful, the demand for green hydrogen for the airfreight industry will rise. EU kerosine demand in 2018 was 62.8 million tonnes[113].

The derived hydrogen demand for 2050 is 120 petajoule liquid hydrogen which is equivalent to 1 Mt and about 30 petajoule compressed hydrogen that equals 250'000 tons hydrogen. Total consumption is projected to 2.85 Mt liquified hydrogen and 0.77 Mt compressed hydrogen by 2050[114].

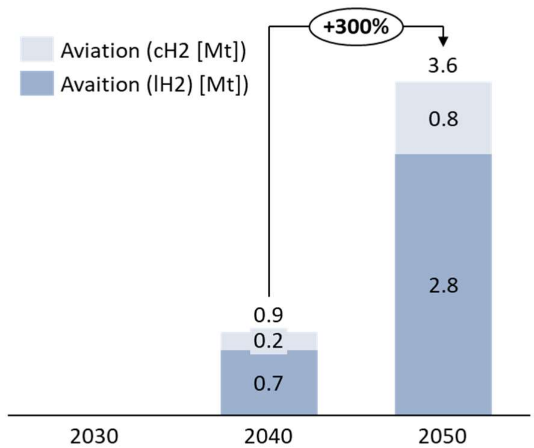

Figure 29: Hydrogen demand forecast for aviation (ambitious scenario)

3.2.7.4 Hydrogen for sea transport

The challenge to decarbonise sea transports is high as the lifetime of ships is about 30 years and for the inland ships the average lifetime is close to 40 years[115]. Retrofitting of the vessels is a time consuming and costly process.

The FuelEU Maritime (FEUM) regulation aims to use at minimum 2% of Renewable Fuels of Non-Biological Origin (RFNBOs). Maersk plans to build an e-methanol production in Spain with 0.39 Mt hydrogen output by 2030 that would equal 3% of EU demand in 2030. Transport & Environment believes that a higher percentage is achievable. In contrast to the costs for volumetric or heavy goods containerised, consumer products will be less effected by the impact of hydrogen based fuels for shipping.

111 European Hydrogen Backbone (2021) "Analysing future demand, supply, and transport of hydrogen", synthetic kerosene uses hydrogen too.

112 Airbus zero-emission programme: www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe (29.01.23)

113 https://www.fuelseurope.eu/dataroom/static-graphs

114 Ballesteros, M. et al. (2022) "Investment scenario and roadmap for achieving aviation Green Deal objectives by 2050", Research for the TRAN Committee, European Parliament, Policy Department for Structural and Cohesion Policies, Brussels

115 Hydrogen Europe (2021) "How hydrogen can help decarbonise the maritime sector", June 2021 https://hydrogeneurope.eu/wp-content/uploads/2021/11/How-hydrogen-can-help-decarbonise-the-maritime-sector_final.pdf

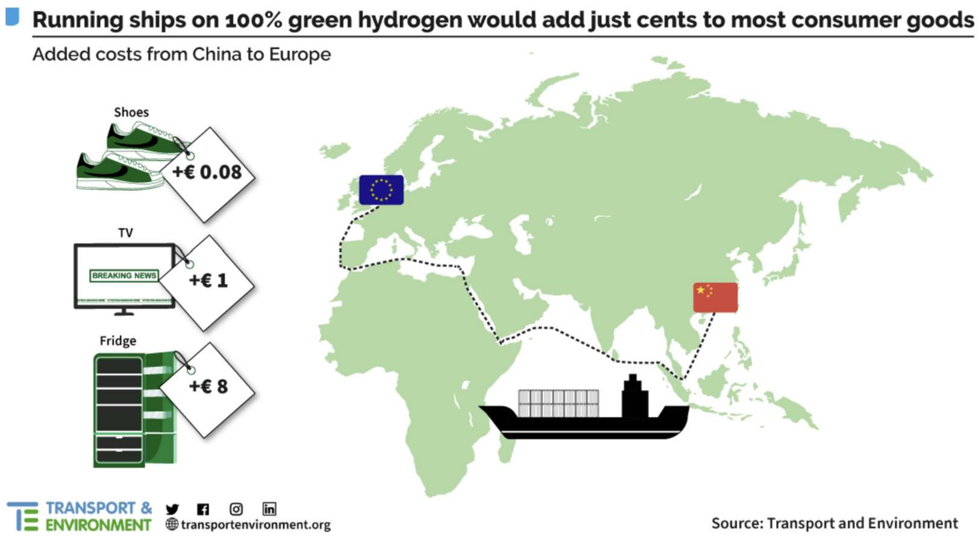

Figure 30: Example of impact of hydrogen-based fuels for shipping[116]

For the estimated savings of external costs through increased use of renewable and low-carbon fuels (RLFs) EU calculates a net benefit of EUR 58.4 bn[117]. The future green fuel choice for the shipping industry is currently undecided. A recent study reveals that the participants can envision more than 10 alternative fuel forms in use in 2050 (see Figure 31).

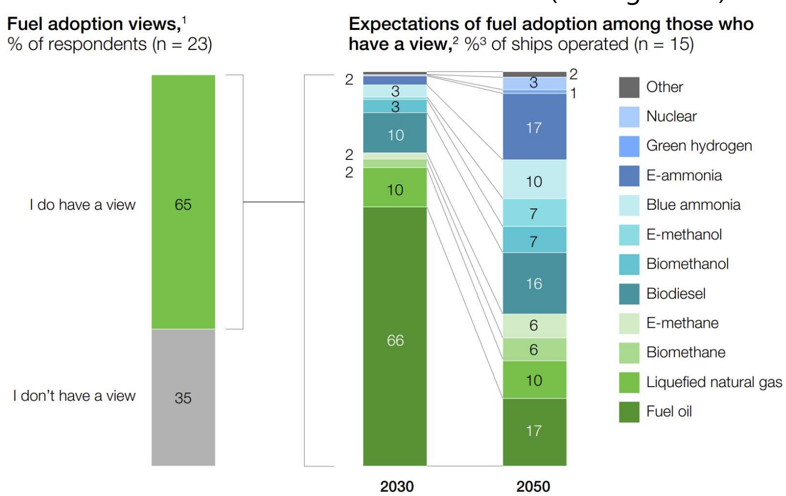

Figure 31: Expectation of a multitude of fuel sources for the shipping industry[118]

Since the future sources of the transition of the sea shipping fuel sources are still uncertain, the demand estimations to decarbonise the shipping industry vary. Larger ships will be part of the ETS certificate trade in 2024[119]. The materialisation will depend on the future technology and hydrogen fuel-based price developments among other factors. For the purpose of this study we estimated a potential of up to almost 10 Mt in 2050 globally (see Figure 32).

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[116] Transport & Environment (2023) "Why and e-fuel mandate for ships? Question & answers (FuelEU Maritime Regulation)", IRENA (2021) "Pathway to decarbonise shipping by 2050"

[117] COM(2021)562 final proposal on "The use of renewable and low-carbon fuels in maritime transport and amending Directive 20009/16/EC"

[118] Maersk Mc-Kinney Moeller Center et al. (2023) "The shipping industry's fuel choices on the path to net zero"

[119] https://www.dnv.com/news/eu-ets-preliminary-agreement-to-include-shipping-in-the-eu-s-emission-trading-system-from-2024-238068

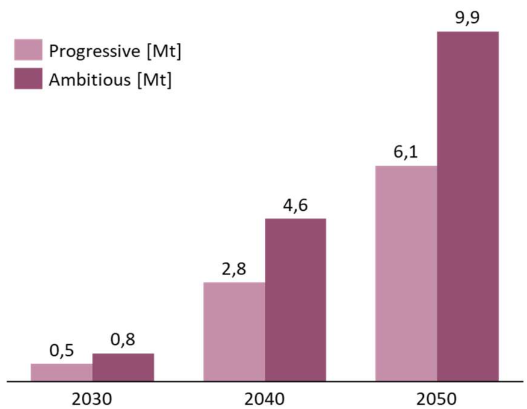

Figure 32: Maximum hydrogen derivates based consumption of water-based transport in Europe[120]

The timing and degree of use hydrogen can be depicted in an impact diagram showing the main drivers that impact the initial price and the price level that will be achieved in 2040 and onwards (Figure 33)[121].

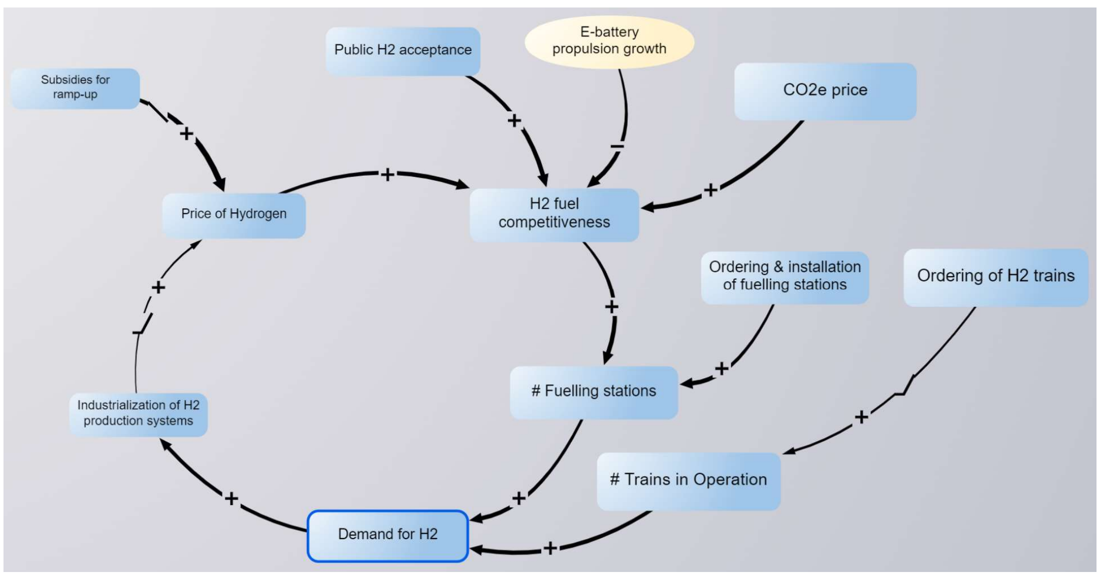

Figure 33: Impact of supply and demand on hydrogen business ecosystem building (own analysis)[122]

3.2.8 Focus on Germany as a relevant importer of green hydrogen

This pre-study focuses on quick but reliable first results. Therefore, we have chosen to limit the EU region to one country which has a relevant hydrogen import need and sufficient research to produce meaningful and tangible initial findings.

Germany qualifies for the following reasons:

1) Relevant importer of green hydrogen (3-4 Mt expected in 2030)
2) Southern Germany is land-locked and will be a net importer of hydrogen with distances > 500 km to the main import markets at the shore

[120] Transport & Environment (2023) "Why and e-fuel mandate for ships? Question & answers (FuelEU Maritime Regulation)"
[121] The calculation of the price development will require more detailed quantitative analysis. The impact factors are a start.
[122] Legend: The relationships with the broken line signify a lagged impact (e.g. 1-3 year before significant impact)

3) High demand for improved resilience and political will to increase energy sourcing independence
4) High number of country specific research available that covers transportation of hydrogen within Germany including last mile analysis

There are several studies that have analysed the hydrogen demand. One focussing on the chemical industry as an early adopter, that can directly use hydrogen as feedstock, shows the distribution of the potential consumers of hydrogen in Germany (see Figure 34).

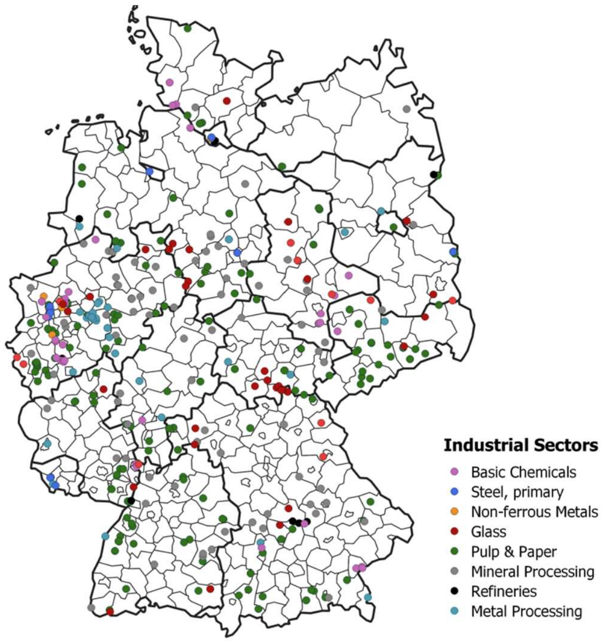

Figure 34: H_2 potential by industry consumer subsector in Germany[123]

The rough-cut demand forecast for Germany and its development is shown below:

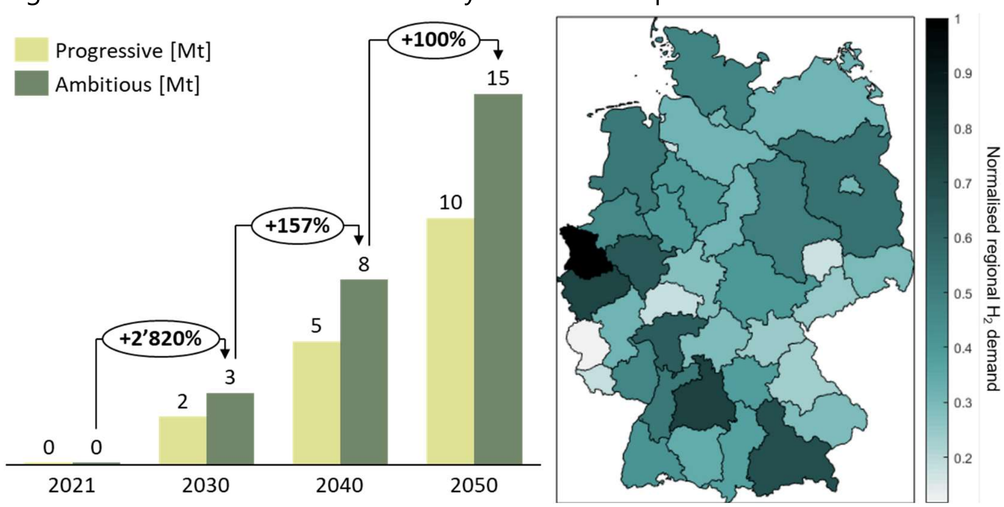

Figure 35: Germany hydrogen demand forecast (own research) and regional demand distribution[124]

[123] Neuwirth, Marius et al. (2022) "The future potential hydrogen demand in energy-intensive industries – a site-specific approach applied to Germany" Energy and Conversion Management (252)

[124] Husarek, Domenik et al. (2021) "Hydrogen supply chain scenarios for the decarbonisation of a German multi-modal energy system", Int. Journal of Hydrogen Energy, 46, 5875-5890; JRC Technical Report (2022)

For chemical basic supply the hydrogen energy equivalent of 35 TWh with upside potential of 80-190 TWh[125] (2050) is forecasted. Other sources project based on a meta study for steel at approx. 26 TWh (2034) to 55 TWh (2050). For the transport sector the main potential is seen to fuel heavy trucks. Car manufacturer Opel pilots with white goods brand Miele in a project to use hydrogen powered vans for service technicians[126]. In total, this accumulates to a hydrogen demand of 9.1 Mt for Germany until 2050 in these three industries only.

The total hydrogen demand and its conversion potential is estimated to be as high as 482–534 TWh/a or about 12.8 Mt hydrogen only for the full decarbonization of the German industry (feedstock and process heat). This would lead to a CO_2e saving of 160 Mt[127]. With the other industries and private consumption, the total demand can be as high as 15 Mt for Germany.

3.2.9 Customer segmentation indication: Localised demand pattern implications

A thorough customer segmentation and demand analysis requires the conversion costs and demand locations. Converting green hydrogen to green ammonia[128] and back to hydrogen requires energy and the related services to be critically assessed to avoid an excess energy demand increase within Europe. The efficiency is reduced if NH_3 is used as an energy vector for transport and then has to be reconverted into hydrogen through a complex process with many energy losses (see Figure 36).

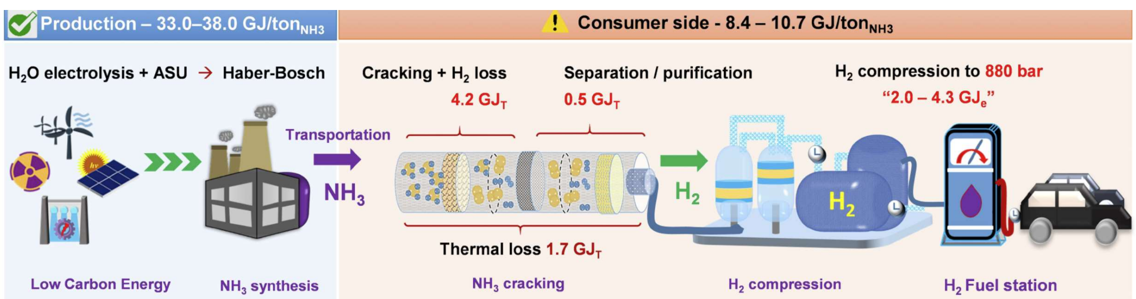

Figure 36: Green ammonia to convert to hydrogen energy consumption[129]

The total added energy consumption shown is between 7-9% or 2.65 kWh per kg/H2 (without process heat) for the reconversion to H_2. If 50% of all imported hydrogen would be via ammonia this will result in an energy demand increase of about 13.25 GW/a of renewable power in 2030 which is an equivalent of about 15 coal-fired plants. Other sources calculate with more than a double of 15-33% energy loss on average based on current technologies[130]. Additionally, ammonia can be directly used as fuel but only for larger infrastructures. Therefore, for

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[125] Wagemann, Kurt (2022) "Zwischenergebnisse der Meta-Analyse", Wasserstoffkompass

[126] https://www.blick.ch/auto/news_n_trends/opels-wasserstoff-chefentwickler-dr-lars-peter-thiesen-es-ist-falsch-nur-auf-eine-technologie-zu-setzen-id18063764.html (19.12.22)

[127] Neuwirth, Marius et al. (2022) "The future potential hydrogen demand in energy-intensive industries – a site-specific approach applied to Germany" Energy and Conversion Management (252)

[128] Wang, H. et al. (2023) "Ammonia-based green corridors for sustainable maritime transportation" in Digital Chemical Engineering (6) consider only ammonia as end product.

[129] Chatterjee, Sudipta et al. (2021) "Limitations of Ammonia as a Hydrogen Energy Carrier for the Transportation Sector" in: ACS Energy Letters 2021 6 (12), 4390-4394

[130] Saygin, Deger et al. (2023) "Ammonia Production from Clean Hydrogen and the Implications for Global Natural Gas Demand", sustainability (15) 1623

decentralised transportation needs (e.g. cars, busses, trucks, trains), there is a potential of direct supply of hydrogen.

The investment trade-off between shipping hydrogen and ammonia must be analysed with these additional criteria in mind from a hydrogen consumer perspective. Next to the cost element of high energy consumption, additional pollution (e.g. NH_x) and the immaturity of the technology of hydrogen crackers[131] at the destination country are to be considered.
A detailed consumer segmentation is recommended for all future energy uses of hydrogen on top of the briefly introduced transport segment to avoid surprises. The transport efficiency is only one part of the equation and should not be overcompensated by conversion bottlenecks at the destination countries (availability of ammonia crackers or green energy supply or impact on green energy prices).

Figure 37 summarises the detailed demand forecast (ambitious scenario). Green hydrogen and derivatives demand is significant already in 2030 and will rise for all industries and application areas in this scenario to a salient contributor of feedstock and energy supply in Europe.

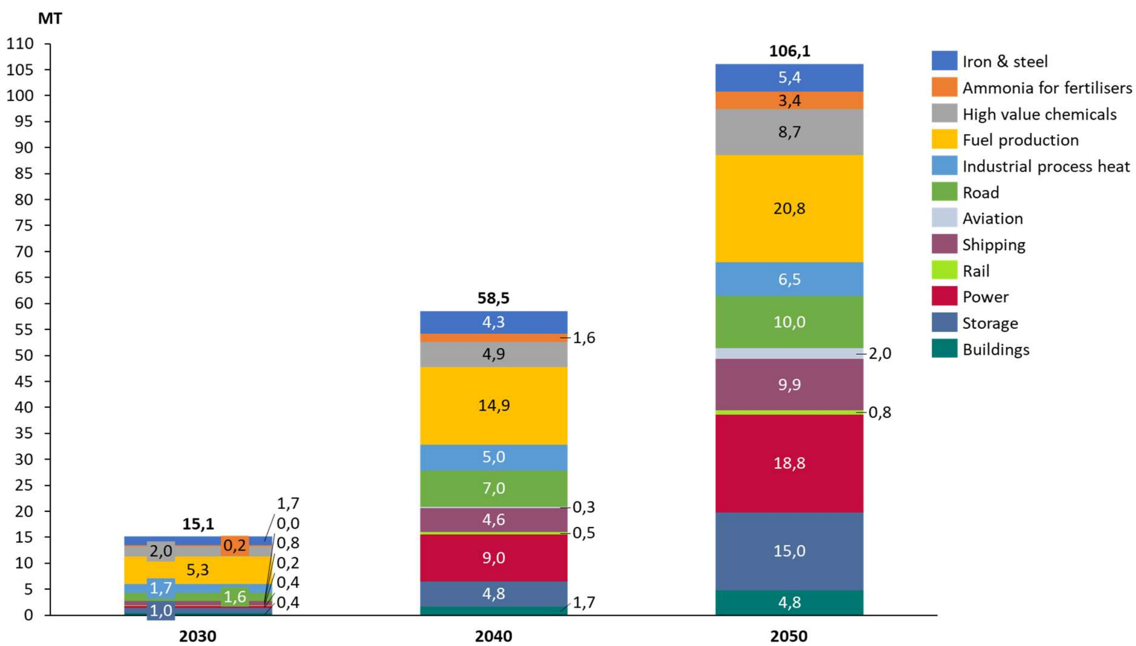

Figure 37: Detailed break-down of volumes (ambitious scenario)

The significant volumes in the transport sector, buildings and fuel production often have decentralised and smaller volume customers. Especially the supply for rail and road in landlocked areas more than 200-300 km away from pipeline access are likely catchment areas.

Iron and steel, fertilizer and chemical production are in particular characterised by fewer and bigger volume customers and often close to (future) hydrogen pipeline networks. Set aside this assumption there are quite a few exceptions that could be eligible customers for hydrogen via combined transport (e.g. ChemDelta Bavaria[132]).

[131] Hydrogen crackers are currently considered at level of 5-8 technology readiness level (TRL) as large-scale crackers are not yet available see Riemer, M. et al. (2022) "Conversion of LNG Terminals for Liquid Hydrogen or Ammonia", Fraunhofer
[132] https://chemdelta-bavaria.de/

3.3 Hydrogen supply sources for the EU market

3.3.1 Global and EU supply gap

Thanks to many announcements the globally expected supply (Announced Pledges Scenario) exceeds the projected supply by 8 Mt (electrolysis) and 2 Mt (fossil fuels with CCUS) by 2030 (see Figure 38).

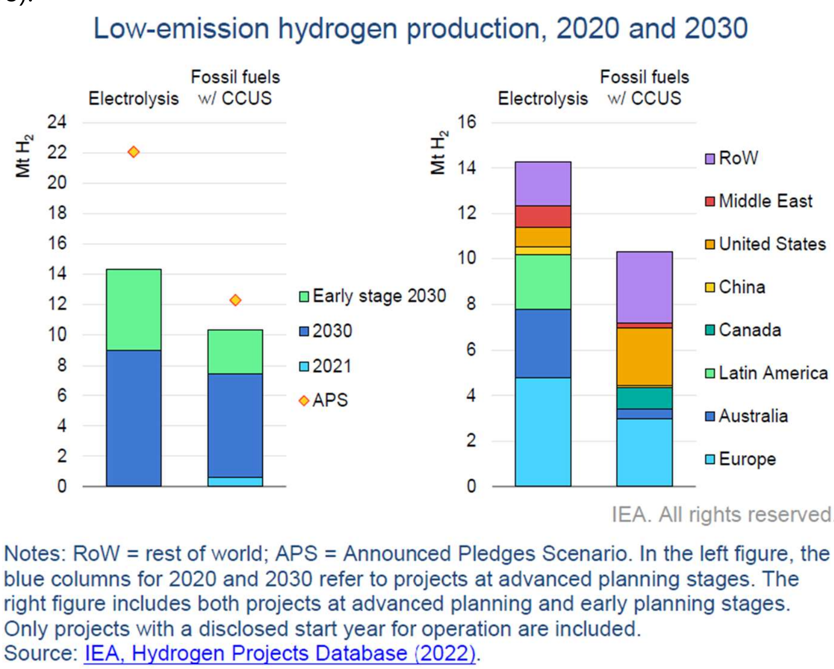

Figure 38: Green and grey hydrogen supply gap forecast for 2030[133]

The forecast shows that the global production of blue (via CCUS) and green hydrogen do not meet the desired demand in 2030. The supply gap is large as the worldwide production in 2030 would not be enough to satisfy the ambitious bottom-up scenario (15.2 Mt) for Europe for green hydrogen. It would even more fail to meet the total EU plans of 20-25 Mt supply for 2030.

3.3.2 Emerging supply sources along the New Silk Road

Since this study focuses on the New Silk Road(s) we analysed the developments along the Central Asian states. The following countries have been considered:

- Azerbaijan
- Kazakhstan
- Turkey
- Armenia
- Uzbekistan
- Turkmenistan

The summary of the scope and status of the projects is compiled in Appendix 11.1. The volume expectation of 13 project announcements in different maturity status in the countries shows

[133] Source: IEA (2022): Global Hydrogen Review, p. 72

that a significant amount beyond 3 Mt of hydrogen production is planned. Of these projects the Hyrasia One project in Kazakhstan is used as a demo case as it was a forerunner in the region.

3.3.3 Transport mode based supply

3.3.3.1 Supply via ports to EU

Hydrogen can be transported via ships to reuse and reapply the LNG infrastructure (existing to be refitted and new ones in building). Fortescue Metals Group Ltd. plans to invest with Tree Energy Solutions 130 million USD to ship 300'000 tons hydrogen to Germany via the Wilhelmshaven port by 2026. They target a production of 15 million tons of hydrogen by 2030 [134]. Similarly, there are plans to import via port of Rotterdam large volumes via sea. Some of the supply solutions do not use rail as a potential solution provider (see Figure 39). The assumption of this future study for Germany is that the majority of hydrogen production is located in the North of Germany or will arrives via the deep sea ports. All hydrogen or derivatives will be shipped to local fuelling stations via road trucks the authors assume.

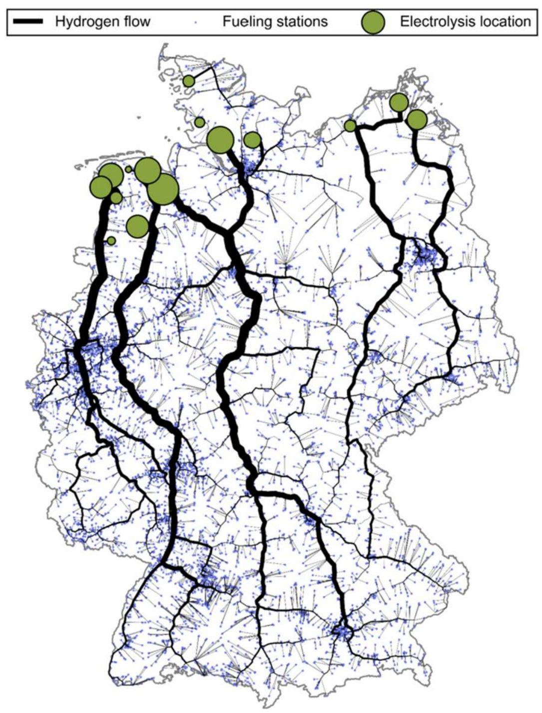

Figure 39: Road-only supply simulation[135] for deep sea supply and offshore production

A first application planned application for rail is to transport ammonia from Belgium to Germany (esp. Belgium Antwerp-Bruge cooperation with Duisport[136]).

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[134] Source: https://www.bloomberg.com/news/articles/2022-10-04/fortescue-doubles-green-hydrogen-spending-as-europe-push-expands

[135] Reuss, Markus et al. (2021) "Hydrogen Road Transport Analysis in the Energy System: A Case Study for Germany through 2050" Energies (14) p. 3166-79

[136] Reconfirmed efforts at the Belgian-German Energy Summit on 14.02.23, https://www.railfreight.com/railfreight/2023/02/17/belgian-german-energy-summit-confirms-rail-corridor-for-hydrogen/?utm_source=newsletter&utm_medium=email&utm_campaign=Newsletter%20week%202023-07, 17.02.23

3.3.3.2 Hydrogen supply via pipelines to EU

There is one planned oil pipeline project proposed form Sangachal (Azerbaijan) to Supsa (Georgia) and one oil pipeline to Cyhan (Turkey)[137]. Another pipeline connecting Turkmenbasy (Turkmenistan) to the Sangachal (Azerbaijan) is projected (Trans-Caspian pipeline). However, the most relevant one for hydrogen is the Baku-Tbilisi-Erzurum pipeline that could connect to the Central Europe Nabucco pipeline. The planning of a conversion to hydrogen is currently not announced. The implementation timelines of these projects is currently difficult to assess.

Pipeline benefits for hydrogen transport are not undisputed. A Fraunhofer study from 2021 points out that H2 via pipelines is not always reliable and safe[138]. A study for the US government identified serious issues with plastic access to the consumers and non-steel pipes[139]. The distribution safety needs to be analysed on a regional and customer group basis.

3.3.3.3 Land-based supply options from Central Asia

The supply from Central Asia is currently without pipeline access to Europe. Therefore, it will be landbound. The only option is bimodal shipments to the regional seaports and then to the European sea ports. The cost estimation, transit time, costs and CO2 emission etc. between the remaining options need to be evaluated. The options to reach inland locations in Europe are (1) long road transit, (2) combined rail-road transport (including rail-shortsea-road for some routes), (3) rail-sea-rail-road transport. These options will be compared after an overview on the gaps and the different scenarios.

3.4 Key take aways from Demand and Supply

Key findings / take aways:

1. Hydrogen can be an important solution for many industries and enable sector coupling to achieve a higher resilience and simultaneously decarbonise hard-to-abate sectors (e.g. transport or steel production) and beyond
2. Despite of many studies the demand variances are very high. We proposed a current demand and supply overview for hydrogen import to be able to identify the needed of supply from Central Asia and the likely destinations. Germany was chosen as suitable destination country candidate.
3. Transport of hydrogen is a critical element that requires the set-up of new infrastructures. Rail and combined transport are not offering services for the full spectrum of demands (e.g. liquid or compressed hydrogen) and rail as transport mode is underrepresented in Europe's current thinking (reports, studies, funding).

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137 https://en.wikipedia.org/wiki/Trans-Caspian_Gas_Pipeline#/media/File:Baku_pipelines.svg

138 Jochen Bard et al. (2021) "The limitation of hydrogen blending in the European gas grid", Fraunhofer Report for The European climate Foundation.

139 https://www.hydrogeninsight.com/industrial/evidence-does-not-support-view-that-existing-gas-network-can-safely-handle-blend-of-hydrogen-and-methane-says-us-government/2-1-1394325?utm_source=email_campaign&utm_medium =email&utm_campaign=2023-02-02&utm_term=recharge&utm_content=hydrogen

4 Gaps of combined transport hydrogen offering

Compared to current efforts the rail industry is not yet prepared to offer international hydrogen shipping services despite a high supply potentials and customers that would demand hydrogen deliveries. For the derivatives like ammonia the situation is slightly better due to existing infrastructure, experience and better commercial conditions enabled by higher energy density.

Reports that focus on the transport of H_2 not even mention rail as an option[140]. Current research focuses mainly on the use of hydrogen as energy source for propulsion of locomotives and wagons.

Value of combined offerings for H2 shipments for the pipeline void areas consists of the aggregation of the movement of multiple containers on the main line (orange colour) using rail as GHG low transport mode (see Figure 40: Combined transport system). The pick-up and the delivery to the customers are done via a short road leg to and from a road-rail terminal.

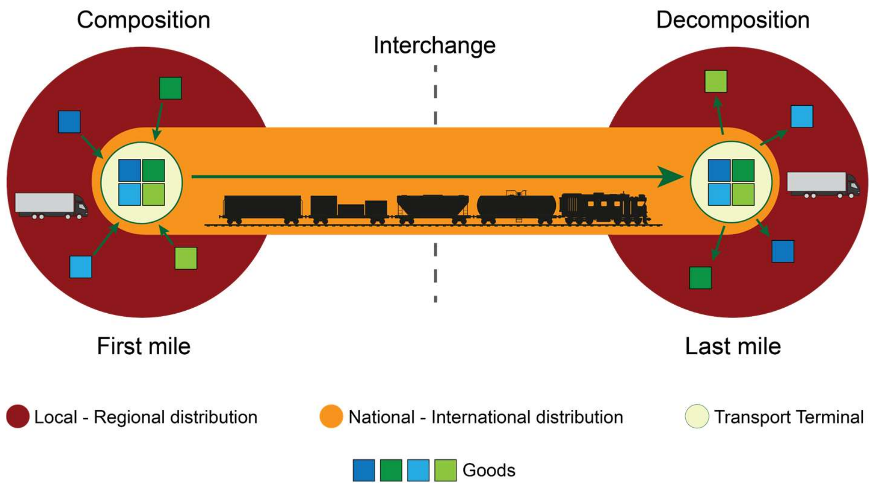

Figure 40: Combined transport system

4.1 Practical gaps in hydrogen business ecosystem in 2022

4.1.1 Business Practice Insight Bertschi Group: Hurdles of hydrogen as fuel

Bertschi Group is a globally operating intermodal chemical transport company. They plan to use green hydrogen to power their own fleet with a carbon-free energy sources in the future, but there is one major gaps that requires closing:

No suitable hydrogen-based traction engines: For the North American axle distance of 5.5-meter offerings for traction engines exist. Currently, there is no off-the shelf offering of hydrogen powered traction engines for the EU dimensions of 3.6 meters available, but. Bertschi

[140] See https://www.reutersevents.com/renewables/renewables/hydrogen-costs-hang-solving-transportation (10.08.22) or IEA (2022): Global Hydrogen Review 2022 (https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf); Guidehouse (2022): Covering Germany's green hydrogen demand: Transport options for enabling imports.

in discussion to explore a solution with some providers. The potential roll-out will depend on the experience of the pilot (mileage performance, maintenance etc.).

The opportunities of hydrogen as good to be shipped in the form of ammonia or hydrogen are possible scenarios for Bertschi. The timing is currently not yet determined and depends on many factors.

4.1.2 Transport engines (Combined Transport)

Bertschi Group interview above revealed a short supply of suitable tractors for combined transport. The technical director of Bertschi is developing solutions that enable combined transport to be able to work with hydrogen as energy source for transportation. This gap is crucial to complete the possibility to have a global transition to hydrogen as propulsion alternative for heavy trucks that do not rely on a trailer to store the hydrogen.

4.1.3 Green energy ramp-up delay (Business Ecosystem)

The build-up of green energy generation within Europe has seen different phases of dynamics. According to the association Solar Power Europe[141] even a 100% renewables power in Europe is possible in their most optimistic scenario. Even if this might be not materialising it stresses the fact, that much more local production is possible.

4.1.4 Shortage of electrolyser capacity (Business Ecosystem)

One often discussed supply gap is the shortage of electrolyser capacity for the green hydrogen production until 2030[142]. The scale-up of electrolyser capacity of 6000-8000-fold (2021 to 2050) is at risk if not supported via suitable policy measures. Some of the new providers are start-ups with the industrialisation risks that the scaling of the small-scale solutions is not a linear path[143]. Promising is the large number of electrolyzer providers consisting of incumbents as well as well-funded start-ups that offers a high likelihood that the supply gap can be solved from 2030 onwards.

4.1.5 Hydrogen shipping experience (Combined Transport)

No operations of H2 transport on rail in Europe <DB Cargo BTT> due to low demand and very high costs of container designs in Germany. The interview with Clean Hydrogen Central and further requests also highlights that currently the shipping on rail is not performed in Europe on rail. It does not surprise due to the low volume of green hydrogen available but

4.1.6 High prices and low hydrogen capacity for containers (Combined Transport)

Despite low carbon impact of the transport today's prices prevent the use of rail as means of transport for small hydrogen pilot projects (e.g. DB regional train pilot in Frankfurt). Instead, it is more economically to use standard trucks. The return on investment cannot be justified for a pilot phase. In general, the prices between 700k to 1.2 Million EUR for the containers seem to be prohibitive for an early test with low volumes (see ch. 5.2). The second gap to be closed is the container payload that is with roughly 1.2 tonnes on average is far below hydrogen

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141 SolarPower Europe and LUT University (2020) "100% Renewable Europe – How to make Europe's energy system climate-neutral before 2050", April

142 Odenweller, Adrian et al. (2022) "Probabilistic feasibility space of scaling up green hydrogen supply", Nature energy(7)854-65

143 Based on literature and Consilis' and Theron's first-hand consulting experience with electrolyzer manufacturing companies

derivates. For road only transports the providers offer fixed trailers with vertical or horizontal tubes. Certification and modifications for rail are possible but this investment has not yet been done by all providers. The containerised transport has not yet been established for combined transport.

4.2 Key take-aways: Need for action to close gaps

The path for combined transport to generate new hydrogen-based business should include the following measures:

1. Identify stable transportation options together with hydrogen hubs, hydrogen capitals (e.g. Duisburg[144] or Rotterdam[145]) and hydrogen regions (e.g. HYPOS in Central Germany[146] or Andalusian Green Hydrogen Valley[147]), existing or new customers that are producing or transform to use green hydrogen in the near term future
2. Rail and combined transport are not offering services for the full spectrum of demands (e.g. liquid or compressed hydrogen). Gaps not only exist for electrolyser capacities, cost-efficient containers but also hydrogen-based traction engines for the road legs of combined transport is currently not market-ready in Europe.
3. Enable hydrogen transportation through real implementation pilots and expand the existing business of derivatives shipments to green hydrogen sources
4. Get involved into R&D investment projects to further optimise the container costs and usability dimensions for compressed or liquid hydrogen

[144] https://www.duisburg.de/microsites/wirtschaft/projekte-themen/Kompetenzregion-Wasserstoff.php
[145] https://www.portofrotterdam.com/en/port-future/energy-transition/ongoing-projects/hydrogen-rotterdam
[146] https://www.hypos-eastgermany.de/
[147] https://www.cepsa.com/en/businesses/commercial-clean-energies/green-hydrogen/andalusian-valley

5 Classification of hydrogen transportation options

5.1 Overview on options to store and transport hydrogen

Hydrogen can be transported and stored in many forms:[148]

1. **Compressed:** Pure hydrogen can be stored and transported as compressed (300 bar, 350 bar, 500 bar, 640 bar, 700 bar, 950 bar, 1000 bar) or liquid hydrogen or as cryo-compressed liquid hydrogen.
2. **Chemical:** It can be stored in different chemical compounds as ammonia (NH_3) or methanol (CH_3OH), bound to another carrier liquid as LOHC, metal hydride and complex metal hydride
3. **Absorption:** Metal-organic frameworks, carbon-based materials, porous organic polymers are mainly relevant for storage only.

Except for the chemical compounds, the other compressed or chemical options are compared in Figure 41. Only compressed hydrogen under 700 bar can reach the efficiency target area of the US Department of Energy (DOE) of 2020.

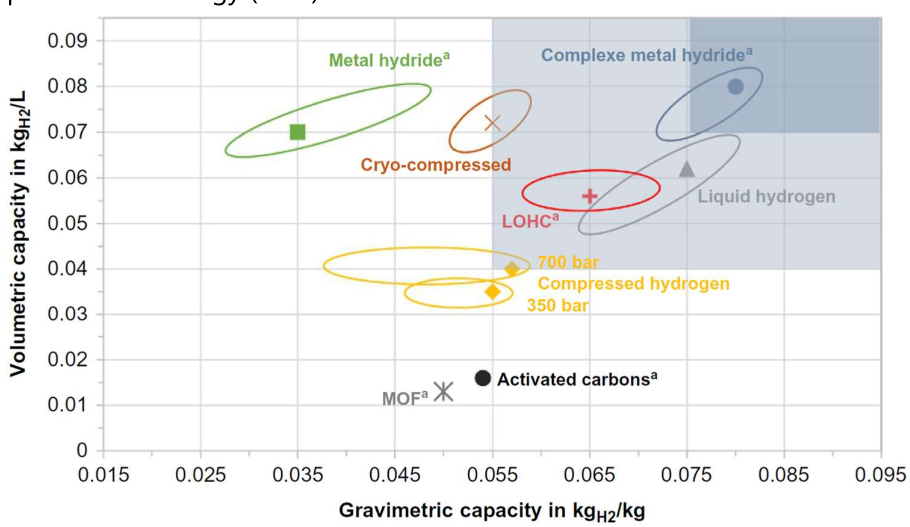

FIG. 5.5 Overview of the capacities of the explained hydrogen storage technologies (*bright gray*: DOE 2020 targets; *dark gray*: DOE ultimate targets) ([a] data for the storage material without the overall storage system).

Figure 41: Hydrogen storage overview options[149]

5.2 Rail transport options

5.2.1 Tank wagons and tank containers for liquids

Tank wagons are currently the most favourable option for shipping ammonia. They can contain a payload of up to 55t and this enables them to ship about 9.5 tons of hydrogen. This form of transporting hydrogen is directly usable for ammonia feedstock (e.g. fertilizer manufacturing). However, it requires centralised or decentralised ammonia cracker stations that currently do not exist in case hydrogen is the required product that customers need.

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148 Langmi, Henrietta et al (2022) "Hydrogen storage" in Electrochemical Power Sources: Fundamentals, Systems and Applications – Hydrogen Production by Water Electrolysis, Elsevier

149 See Azzaro-Pantel, Catherine (2018) „Hydrogen Supply Chains – Design, Deployment and Operation" p.192

Tank containers are also an option, but they are less frequently in use and offer less capacity. For these reasons logistics service providers prefer to use tank wagons for shipments to customers that can receive trains at their site.

The situation for customers without rail track access needs to be analysed in more detail. Judging from the feedback of our interview partners the green ammonia container business has not yet developed.

5.2.2 Craneable containers for cH_2

5.2.2.1 20" and 40" Container options

Multi-element gas container (MEGC) of different types exist to transport pressurised hydrogen. Figure 42 depicts two relevant types (2+4) of containers on the example of NPROXX as one provider for type 4 (carbon composite) containers. The price increases inversely with the weight per kg hydrogen. For hydrogen the weight component is usually less problematic but for the full flexibility on the New Silk Roads a weight below 28 tons is favourable under current conditions.

Bild 2: Beispiel MEGC mit Typ 4-Zylindern (www.nproxx.com)

Tabelle 1: Typische Daten für MEGC

20ft-Container	300 bar	300 bar	500 bar
Zylindertyp	Typ 2	Typ 4	Typ 4
Speicher-kapazität	312 kg_{H2} (300 bar)	371 kg_{H2} (300 bar)	518 kg_{H2} (10-500 bar, 15 °C)
Leergewicht	21 t	9,25 t	14 t
Preis pro kg_{H2}	Ca. 480 €/kg	Ca. 670 €/kg	Ca. 740 €/kg

Figure 42: Example for 20-foot container compressed hydrogen options[150]

The actual pricing will see high improvement potential. NPROXX announced on the Hannover fair in 2023 an increase of payload by 20% plus a cost reduction of 20% which will increase the likelihood to identify robust business models.

Research papers target 300 USD / kg H2[151] or 282 € / kg which can make transport of compressed hydrogen more reasonable. The realistic assumption with an increase of the volume due to higher pressure per 40ft container would be 250 € / kg as future target until 2030. With this price trajectory the price is around 325-375 kEUR, which is about 2-3 times of that of a tank container.

[150] Dorothee Lemken, Joachim Jungsbluth, Georg Dura und Christian Spitta (2021) Wasserstoff-Bunkern in der Binnenschifffahrt
[151] Houchins/James (2022) "Hydrogen Storage Cost Analysis"

Further optimisations can be expected if the know-how from other transport modes is transferred to rail. The Kawasaki company is working only on road and sea but are willing to explore a qualification to rail if the demand is articulated.

5.2.2.2 Liquid hydrogen containers (LH2)

Liquid hydrogen offers the better weight to volume relation but has a negative boil-off side effect that needs to be evaluated[152]. There are several projects to explore the rail transport of cryogenic liquid hydrogen. BTCs for liquid hydrogen are developed to contain a payload of about 5 tonnes of hydrogen but currently not in use.

Deficits are the ultra-low temperature of below -233 °C, the specific infrastructure needed and the energy loss that is higher compared to compressed hydrogen. The energy requirement is roughly triple the amount for compressed hydrogen or about 30% of the shipped energy value of hydrogen[153].

5.2.2.3 BASF BCTs

BASF is developing its own standard for containers called BASF Class Tank (BCT) container. They maximise the volume and weight allowances. With the existing model up to 5 tonnes of lH2 are possible but currently this option is not actively in use.

The benefit of larger containers and a solution to improve the filling process currently in the patenting process has the potential to improve the business case for combined transport. A limitation is the increased weight of the containers that will require some additional infrastructure investments (cranes, wagons, etc.) to be able to ship more than 28t containers.

5.2.3 Recommendations

Craneable containers to comply with EU regulations and maximum flexibility for the New Silk Roads will increase interoperability and efficiency and attractiveness towards a shift-to-rail.

	H2 (640bar)	**LH2 (cryogenic)**	**Ammonia**	**LOHC**	**SIHC** (Metal hydride)
Price (as-is)	6-8-times higher	4-6 times higher	100k-300k	tbd	5x higher
Price (with innovation / kg)	2.5-5 times higher				
Energy density (kWh/l)	1.4	2.4	3.6		
Key hurdles	Medium Energy consumption (about 12% of HHV)	High Energy consumption (about 30% of HHV)	High Energy consumption (if converted to H_2)		
Readiness	TRL9	TLR 7-8	TLR9	TRL 8?	???
Assessment	+++	++	++++	++	+

Figure 43 – Comparison of transport and storage container options per hydrogen derivate[154]

[152] Ustolin, Frederico et al. (2022) "An Extensive Review of Liquid Hydrogen in Transportation with Focus on the Maritime Sector" Journal of Marine Science and Engineering (10), 1222

[153] Langmi, Henrietta et al (2022) "Hydrogen storage" in Electrochemical Power Sources: Fundamentals, Systems and Applications – Hydrogen Production by Water Electrolysis, Elsevier

[154] Expert interview-based data collection

The opportunity to explore bigger tanks (e.g. BASF BTCs) is another opportunity for liquid hydrogen to become more cost-competitive if the higher weight can be transported throughout the complete route via all New Silk Road variants.

5.2.4 New Silk Roads for combined transport

The New Silk Roads have been a success for the combined transport sector. There has been further effort to explore other routes due to the Russian-Ukraine war. Next to the established Northern routes the Middle Corridor has gained serious attention.

In case of continued sanctions and for resilience reasons the further expansion of the Middle corridor is of value. Associations such as TITR organise its advancement (see Figure 44). The traffic in the countries in Central Asia is growing (e.g. Kazakhstan[155]).

Figure 44: Middle Corridor routings according to TITR[156]

5.3 Pipeline systems availability and expansion plans

Pipelines are a proven and effective means for transport of liquid and gaseous goods. Blending of 10-20% hydrogen into an existing methane gas pipeline is often possible without much retrofitting investments. Even 30-40% of hydrogen content only demand limited investments for adaptions. Blended mixtures of hydrogen and natural gas can be used for heating and power generation purposes. This common understanding is not undisputed and may require some deeper analysis that limits the near-term pipeline capacity and may require other modes of transport[157].

If the end use of the H_2 is requiring pure H_2 (e.g. combustion or material use as feedstock) then pure hydrogen pipelines are required. There are existing regional hydrogen pipeline networks, which are presently not connected to each other. Build-up, reuse or retrofitting existing gas pipelines will take time and some regions are currently under war restrictions which limits the

[155] https://www.railjournal.com/freight/freight-traffic-sets-new-records-in-kazakhstan/

[156] Trans-Caspian International Transport Route (TITR) (https://middlecorridor.com/en/)

[157] See some evidence for the US Topolski, Kevin et al. (2022) "Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology", NREL and Fraunhofer questions the value due to a 43% cost increase for a 6-7% emission reduction in Bard, Jochen et al. (2022) "The Limitations of Hydrogen Blending in the European Gas Grid", Fraunhofer, https://www.hydrogeninsight.com/industrial/evidence-does-not-support-view-that-existing-gas-network-can-safely-handle-blend-of-hydrogen-and-methane-says-us-government/2-1-1394325?utm_source=email_campaign&utm_medium=email&utm_campaign=2023-02-02&utm_term=recharge&utm_content=hydrogen

predictability and realistic availability of pipelines for some regions between EU and Central Asia.

5.3.1 Pipeline system development in Europe and Germany

The hydrogen pipeline system for Europe is scheduled to be extended by 2030 (see Figure 45~~Figure 45~~).

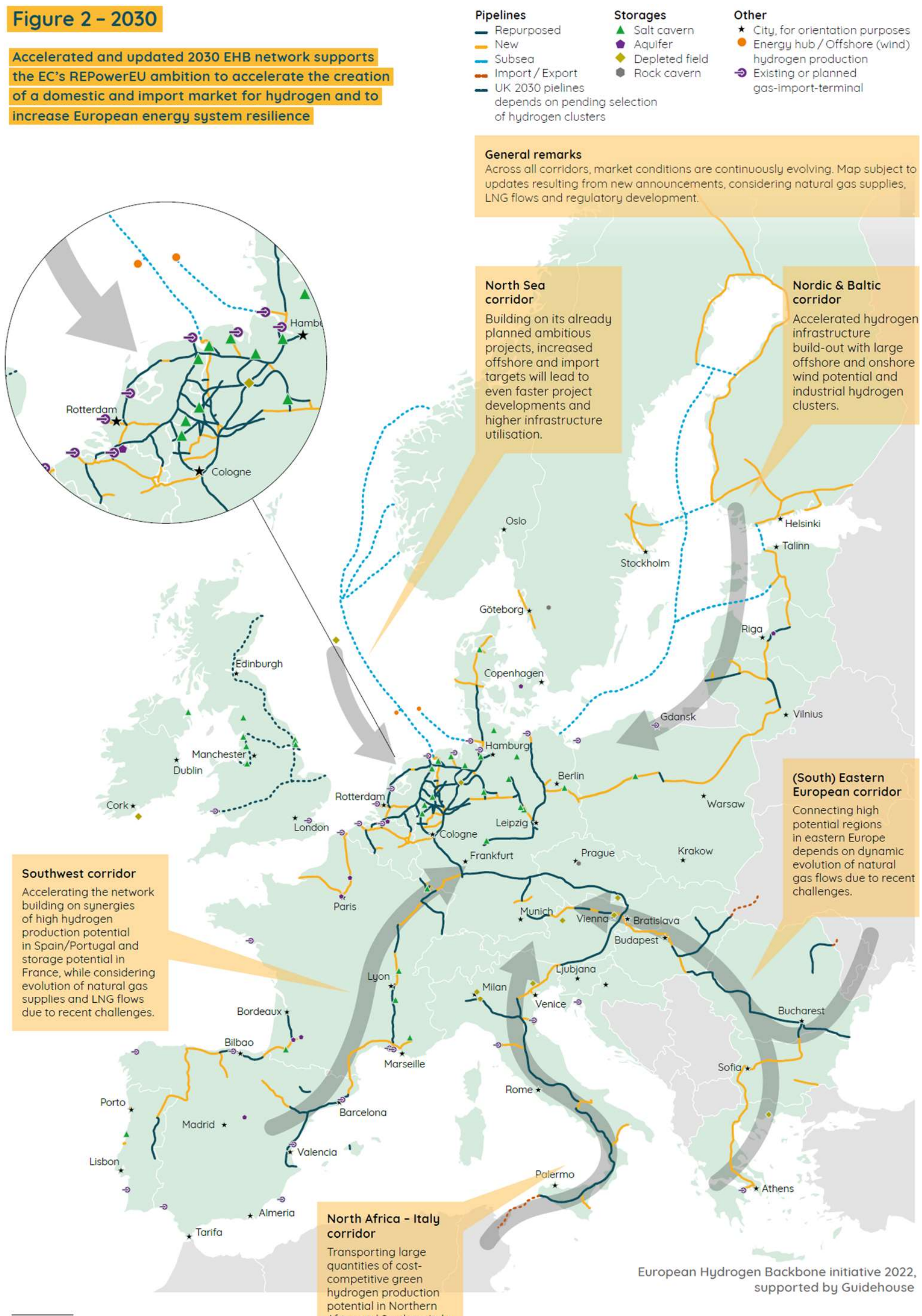

Figure 45: European Hydrogen Pipeline System expansion plans

The planned expansion by 2040 is more complete, it still shows white spots (in red for DE):

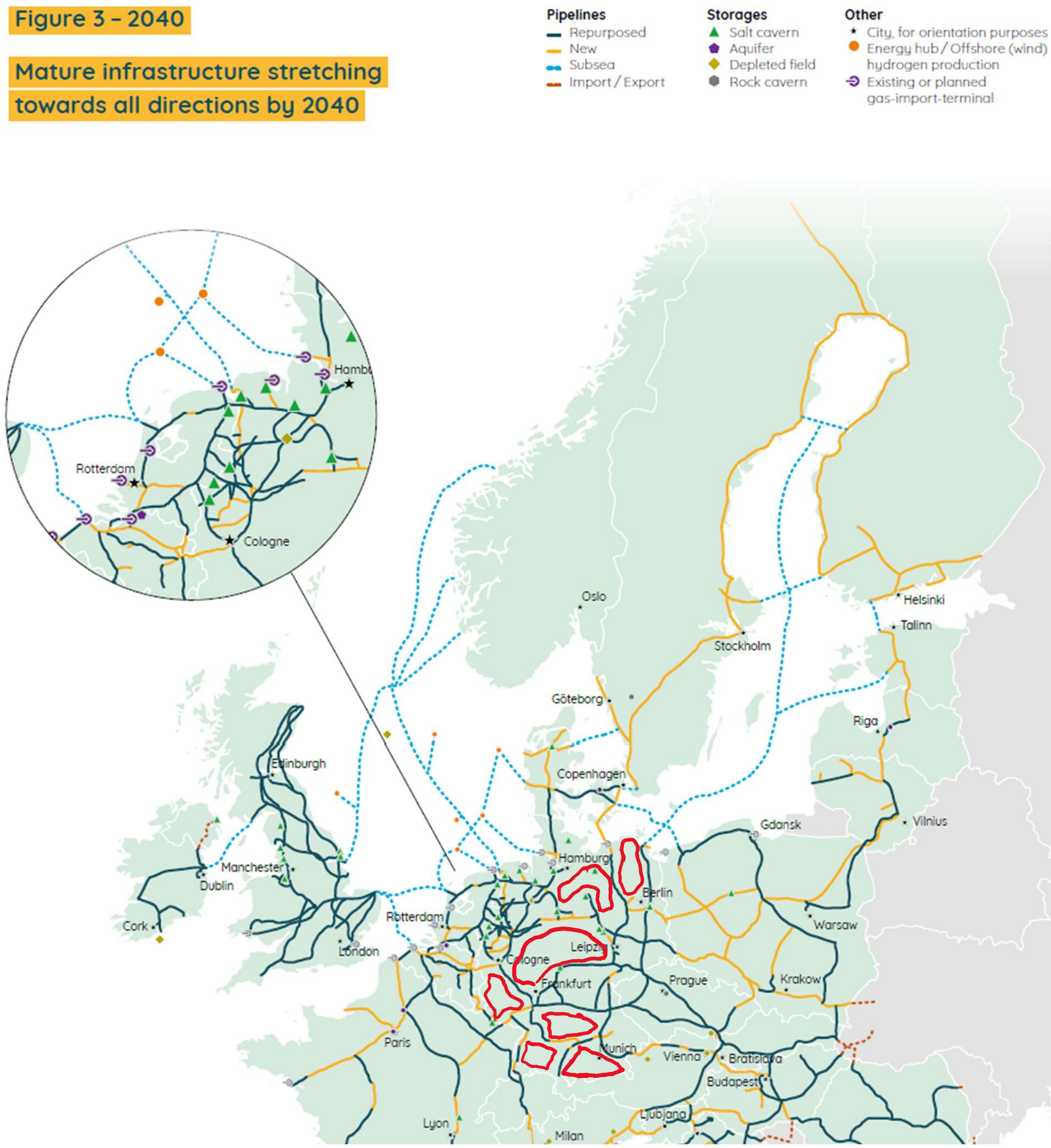

Figure 46: Pipeline gaps in 2040 (in red)[158]

The request of the gas pipeline industry was not yet followed by the EU. The current direction is that the gas and hydrogen network will be kept separately (two-infrastructure pathway)[159] for regulatory clarity but that is likely to impact the fast build-up of a hydrogen network. Hence, areas with no direct hydrogen pipeline access might exist for longer and the plan is at risk to

[158] Guidehouse (2022) "European Hydrogen Backbone – A European Hydrogen Infrastructure Vision Covering 28 Countries"

[159] Banet, Chaterine (2023) "BUILDING EUROPE'S HYDROGEN AND RENEWABLE GAS MARKETS", CERRE Report

be realised with delays. On the receiving side in Germany many areas will not be covered within the next 15 years as the simplified overview highlights (see Figure 46).

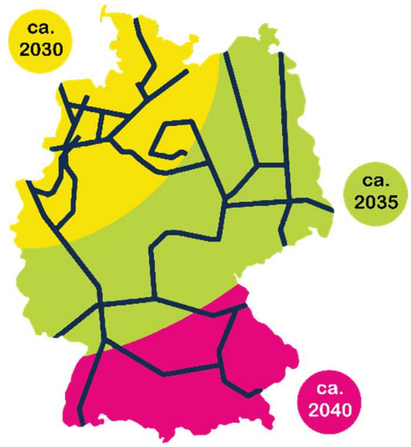

Figure 47: Pipeline ramp-up in Germany [160]

New pipeline projects are under development with yet to be assessed impact and progress. Some of the most relevant ones are:

1) Hydrogen Interconnector Bornholm-Lubmin (2027)
2) Norway to Germany pipeline
3) Spain to Central Europe

5.3.2 Pipeline development in Central Asia

Under current Russia-Ukrainian war situation a completion of a pipeline building through this area is unlikely within the next five years. In addition, pipelines are not always suitable for every need due to some trade-offs:

1) Hydrogen pipelines longer than >5000[161] or > 7000 km are deemed to be inefficient due to a larger loss of energy during the transport.
2) Pipelines fit only for large volumes (> 1 Mt/a)
3) Pipelines do not allow to gradually grow volume
4) Pipelines do not reach to the consumer (with a few exceptions of very large ones)
5) Hydrogen pipelines can be more expensive to operate than natural gas ones[162]

Next to the road, road-rail and road-rail-short sea connections via the Caspian Sea there is the possible alternative to connect via the North-South Corridor towards to the seaport Bandar

[160] Interview with DB BTT Cargo, https://www.dvgw.de/themen/energiewende/wasserstoff-und-energiewende/h2vorort and confirmation from other sources e.g. Guidehouse (2022)

[161] Bossel, U and Eliasson, B. (2003) “Energy and the Hydrogen Economy”, Alternative Fuels Data Center (AFDC) Report USA, Langmi, Henrietta et al. (2020) “Hydrogen storage”, In Electrochemical Power Sources: Fundamentals, Systems, and Applications (pp. 455-486). Elsevier

[162] Some authors state this whereas other assume the same costs which implies that a case-by-case analysis is required

Abbas and ship via short sea to the hydrogen hubs of Oman at Duqum HyPort[163] or Hydrogen Valley at Sur[164] and Dubai[165]. However, the political risk of an unstable Iran must be considered.

5.4 Comparison of shipping options for land-based transport

The transport costs are a key driver of how the import of hydrogen or derivatives will be organised for a future proof hydrogen business ecosystem transformation. The following initial logic helps to identify the "sweet spot" for shipment of hydrogen via road-rail:

1. Identify the **hydrogen compound** and average **volume** that customers will want to source
2. Estimate the **aggregated demand** for the region
3. Choice of means of transport (e.g. container or specialized wagon)
4. Identify the **location clusters** and the levelized cost situation (e.g. proximity to harbours or pipelines versus landlocked locations)
5. Estimate the **cost level and cost level development** based on the infrastructure development for the identified regions
6. Decide on the **stability of shipments via rail**: (1) will it be the standard form of supply or (2) reserve capacity or (3) only exceptional if more cost and environmentally efficient transport modes are temporarily or longer term not available (e.g. due to a war or terror situation)

One simplification is made: The last mile costs are excluded as they are not available for the other modes of transport except for the situation where the hydrogen consumer has direct access to a pipeline or port. For combined transport this last mile transport can be short and with the planned expansion of the terminal density until 2050 this can be less than 50 km to cover the all geographic regions in Europe.

	Road	Rail	Pipeline
Shipping costs	3.5 EUR per kg	3 - 5 EUR	0.32 EUR per kg
Capital costs	217 TEUR	261 TEUR	709 TEUR
Operational costs	40.6 €/h	23.6 €/h	0.058 €/kg/day
Average speed	55	45	
Loading / Unloading time	2	12	
Fuel efficiency	3.58 km/l	10.13 km/l	
CO2	37g / kg		
CO2 cost savings		- 0.0044 / kg	
Preference Sequence	3	2	1

Figure 48 – Cost comparison for a 600 km distance for landbound cH2 shipments[166]

[163] https://www.omanobserver.om/article/1110483/business/energy/duqm-port-primed-to-be-omans-leading-green-hydrogen-export-hub; Green ammonia plant to be operational in 2027 for 330000 tons/a capacity: https://www.zawya.com/en/projects/industry/ministry-outlines-plans-to-make-oman-a-global-green-hydrogen-hub-a0xqkb1o

[164] https://fuelcellsworks.com/news/hy-fly-to-support-growth-of-hydrogen-hubs-in-oman/

[165] www.rolandberger.com/en/Insights/Publications/Hydrogen-Powering-the-Future-of-Mobility-in-The-Middle-East.html

[166] Robles, J.O. et al. (2018) "Hydrogen Supply Chain design: Key Technological Components and Sustainable Assessment" in: Azzaro-Pantel, Catherine "Hydrogen Supply Chains – Design, Deployment and Operation", Academic Press

The relationship is much more in favour of rail for ammonia shipments where the transport costs are lower but if the end user demands green hydrogen, then the cracking infrastructure, energy loss and additional conversion and transport costs need to be calculated. We will cover part of this in chapter 6.

5.5 Take-aways on hydrogen transportation options

The challenge is to identify the most viable transport options for green hydrogen and its derivatives. Multiple options with different properties exist:

(1) for pure hydrogen (e.g. compressed at 500/640/700 bar or liquid) or
(2) choice of a hydrogen derivative chemical compound (e.g. ammonia or methanol)
(3) LOHCs
(4) Metal hydrides

Despite multiple interviews with several producers of containers, leasing companies and shippers there seems to be no universally applicable solution. Key criteria for the choice are:

(1) Ability to schedule
(2) Set-up time
(3) Customer requirements
(4) Costs

Pipelines are not suitable for all hydrogen volumes and the network expansion will at minimum take 17 years to for regions of in Germany. Other regions of the EU will face the same situation.

Rail-road transport has a niche to fill and to fulfil a salient contribution to the decarbonisation of rail transport but even more for the decarbonisation of the European economy. This role seems to be underrepresented.

6 Assumptions and hydrogen scenarios from Kazakhstan

6.1 General assumptions

The future use of hydrogen depends on a multitude of factors (e.g. progress on green energy build-up, electric battery developments). The focus on the "progressive" and "ambitious" scenarios can be substantiated. The innovation potential for green hydrogen is large as the learning curve and economies of scale have not yet materialised compared to lithium-ion batteries (97% cost decline from 1991-2020) (see Figure 49) or photovoltaic cells that have seen impressive improvements.

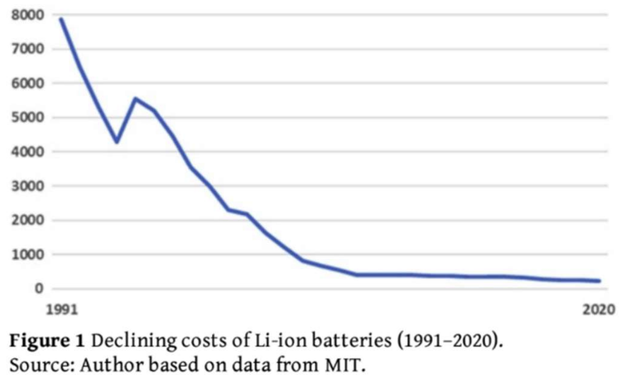

Figure 49 – Lithium-ion cell price decline (USD/kWh)[167]

Both scenarios are based on a paradigm shift with renewable energy to gradually supersede the centralised fossil fuel-based and automobile driven 4th paradigm[168] of the 4th Kondratjew cycle to develop the 6th paradigm based on renewable energy[169]. This implies not only a technical but also a social and behavioural major change ahead. On a positive assumption that Europe and the world is on a promising path to achieve these major changes, we develop the possible scenarios for the import of hydrogen from the chosen region of Kazakhstan to explore the conditions for the feasibility and roadmap planning.

6.2 Choice of detailed scope

This study focuses on the Eurasian hydrogen potential from Central Asia to Europe. For a pre-study we simplified the specific focus onto one relationship that is representative and has a high likelihood of being implemented. We choose one of the most advanced hydrogen projects in Kazakhstan as source due to its significant size and already high awareness in the European Commission (see MoU[170]). Further, Kazakhstan is land-bound meaning it has a much shorter land and short-sea connection to Europe than via deep seaports. Thirdly, we choose Germany as destination country as it is a large consumer of green hydrogen (approx. 4 Mt by 2030) and an expected undersupply due to a lack of internal capacity of low-cost renewable energy which makes it a large net importer of green hydrogen and its derivatives.

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[167] Mathews, John (2023) "A Solar-Hydrogen Economy-Driving the Green Hydrogen Industrial Revolution", Anthem Press

[168] Mathews, John (2013) "The renewable energies technology surge: A new techno-economic paradigm in the making", in: Futures (46) p. 10-22

[169] Mathews, John (2023) "A Solar-Hydrogen Economy-Driving the Green Hydrogen Industrial Revolution", Anthem Press.

[170] MOU between EU and Kazakhstan on 07.11.22 https://ec.europa.eu/commission/presscorner/detail/da/statement_22_6648

The process in focus are shipments of hydrogen and ammonia including the required conversion processes from the place of production to the destination (see green areas in Figure 50). This complements most studies that focus on the levelized cost of production from renewable energy sources (RES) to the electrolysis.

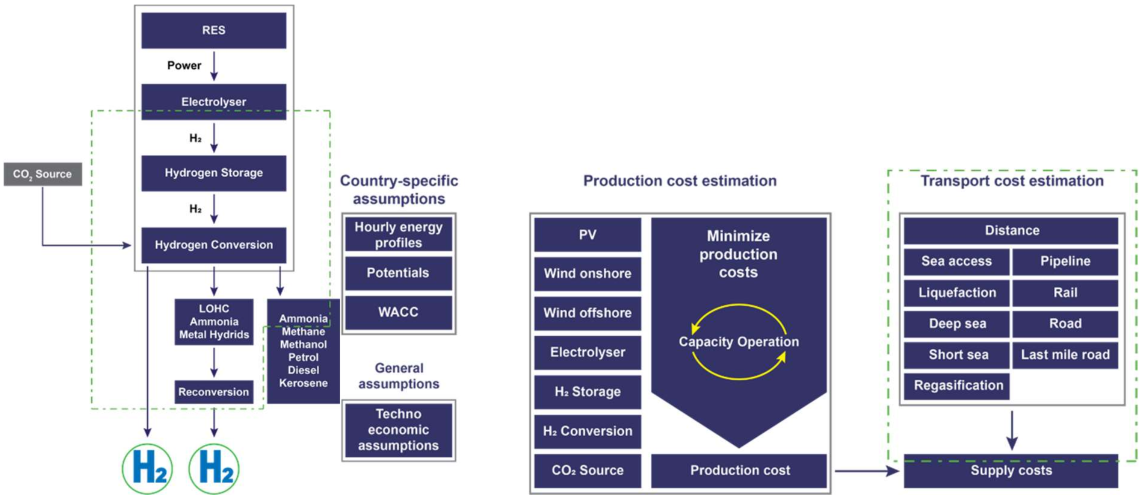

Figure 50: Process focus area of this pre-feasibilitystudy[171]

6.3 Practice case: Hydrogen production project HYRASIA ONE

Germany-based SVEVIND Energy Group (the project developer of the HYRASIA ONE project in Mangystau Region, Western Kazakhstan, www.hyrasia.energy) plans to produce 2mn t/a Hydrogen (with equivalent of 11mn t/a Ammonia) with envisaged production start in 2030 and ramping up capacity within 2-4 years.

SVEVIND is considering selling about 50% (ca. 1mn t/a H2 resp. 5.5mn t/a NH3) each to European and Asian Markets (domestic market and Southeast Asia namely China, India and Japan, Korea). Due to the landlocked site close to the port of Kuryk, Mangystau region, deep sea shipping is not easily accessible, and hence rail (northern and southern routes) or ship-rail transport (e.g., middle corridor via the Persian Gulf or Caspian Sea & Black Sea) are currently the most viable transport options in the absence of dedicated hydrogen pipelines in the foreseeable future.

The current logistics concept is to use tank wagons for green ammonia and use the middle corridor, south corridor and/or the northern corridor by the start of the project. Transporting pure hydrogen by ship or train has been economically refuted.

One key success factor for any green hydrogen project globally is customer and/or government offtake agreements or guarantees to be able to set up a sound business case to justify a EUR40-50bn investments.

[171] Moritz, A et al. (2022) "Estimating global production and supply costs for green hydrogen and hydrogen-based green energy commodities" Int. Jour. of Hydrogen Energy

6.4 Cost factors and external effects assumptions

6.4.1 Hydrogen production costs

Green hydrogen production costs are the starting or stopping point for green hydrogen business ecosystem transformation. The costs for hydrogen from IRENA are highly dependent on the energy production costs largely consisting of a combination of solar and wind energy (see Figure 51).

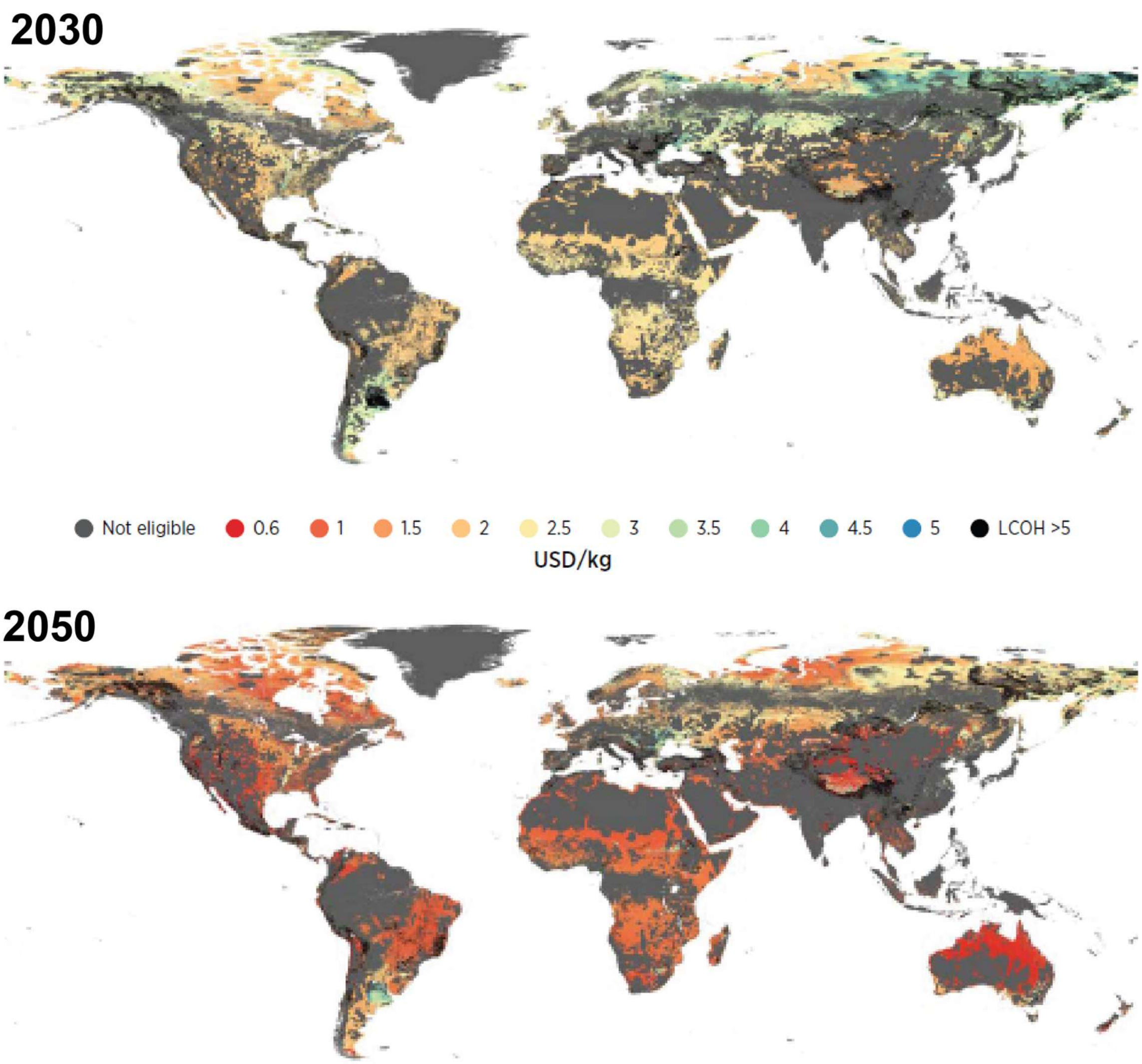

Figure 51: Levelized costs estimations by IRENA (2020)[172]

Even in not so favourable places like Germany not all photovoltaic potential has been used and photovoltaic power can reach even in the winter season a non-neglectable amount (e.g. 1 TWh)[173] that is equivalent to substitute about 3-4 average coal power stations.

[172] IRENA (2022) GLOBAL HYDROGEN TRADE TO MEET THE 1.5°C CLIMATE GOAL – Part1 , p. 20

[173] Stöcker, Christian (2023) „Zwei spektakuläre Visionen – Beide sind falsch“, Spiegel Online

6.4.2 Shipping costs projections for deep sea and pipeline

There is a large number of landed cost calculators that suggest they can visualize the hydrogen supply costs globally (e.g. EWI[174]) but the ones analysed oversimplify the supply chain modelling leading to significant errors[175] by not considering the supply chain routes.

Some authors estimate that green hydrogen and green ammonia will be together with bio-methanol the most price attractive fuel sources to decarbonising shipping[176]. Transport costs of green hydrogen vary greatly. The studies analysed range from very positive to expensive scenarios that often do not include rail as transport option (see Figure 52+Figure 53).

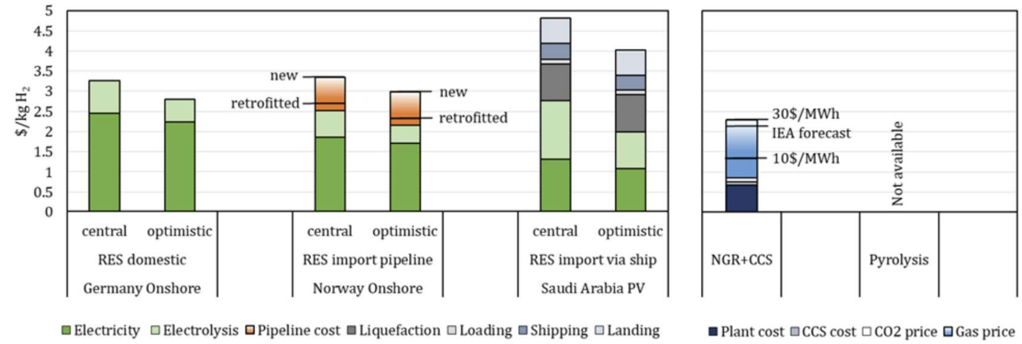

Figure 52: Comparison of shipping costs for hydrogen (pipeline vs deep sea) from EWI [177]

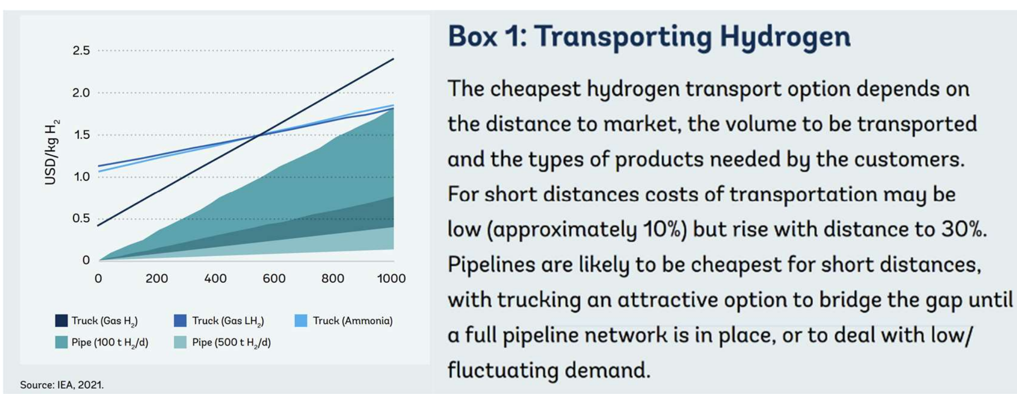

Figure 53 – Shipping cost comparison (without rail-road option) from IEA [178]

Attention must be given to the figures presented above as conversion cost for shipping after landing at the port may not be complete (only storing not transforming) and transport costs to destination are missing (longer last mile up to 1000 km). In addition energy prices in Germany are based on 2020 prior to Ukrainian war and the sea route from Oman and are likely too low and not 100% green energy.

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[174] Braendle, Georg (2020) "Estimating Long-Term Global Supply Costs for Low-Carbon Hydrogen", EWI Working Paper

[175] We performed a spot check with the Hyrasia One project in Kazakhstan with the following deficits: (1) Sea distance is 105% to short (6'601 km model distance vs 13'533 km real distance (via Oman to Hamburg), (2) a direct sea connection does not yet exist. It can only be implemented via the seaports of Dubai or Oman using a pipeline or rail transport, (3) hydrogen production is modelled at the capital city, but it will be close to the Caspian Sea (about 2300 km distance). (4) Pipeline transport to neighbouring countries is currently less likely due to conflicts with Iran and Russia.

[176] Culliane/Yang (2022) Evaluating the Costs of Decarbonizing the Shipping Industry: A Review of the Literature

[177] Braendle, Georg (2020) "Estimating Long-Term Global Supply Costs for Low-Carbon Hydrogen", EWI Working Paper, 20/04

[178] Moreira, Susana and Laing, Tim (2022) "Sufficiency, sustainability, and circularity of critical materials for clean hydrogen", World Bank

6.4.3 Levelized costs of green hydrogen (LCOGH) and cost of transport

The LCOGH is frequently used in the literature and reports on green hydrogen. It can be defined as indicator how much it costs to produce 1 kg of green hydrogen, taking into account the estimated costs of the investment required and the cost of operating the assets involved in its production[179]. More technically termed it is the discounted cash flows of the total operations costs (investment, operations, fuel costs, carbon price, maintenance and service costs) divided by the discounted hydrogen output[180]. Often technological parameters such as conversion efficiencies, lifetimes and annual utilisation factors are also integrated[181].This production cost needs to be complemented by the customer-supplier relationship related logistics costs. Since the focus of our study is the logistics supply chain we focus on the later part of the model and estimate the logistics costs starting from today’s baseline.

6.4.4 Holistic assessment of hydrogen impact including external effects

Cost factors and CO_2 pricing are only two key drivers that define the future development of the hydrogen business ecosystem. Other external effects must be considered to identify the full impact to achieve a comparable level different transportation modes.

External costs or externalities are arising when the social or economic activities of one group of persons have an impact on another group in a way that the impact of the first group is not fully compensated. The costs are not borne by the transport client or user and therefore are not taken into consideration in the decision but have a negative impact on other parts of the society (social costs)[182]. The generic ways to mitigate these negative effects are through (1) regulation or (2) market-based instruments (e.g. taxes, emission trading) or (3) combinations thereof (e.g. taxes on Euro emission classes of vehicles).

Additional factors to be considered here in a holistic calculation are at minimum noise, NOx or hydrogen emissions, climate change, congestion, accidents, resource scarcity, habitat damage and other pollution (e.g. soil and water). A factor not always considered is the **energy consumption of the mode of transport**: Rail has an advantage of up to 72%[183] less energy consumption compared Diesel trucks and more than 50% less compared to e-trucks on road[184]. In terms of greening transport this modal shift can be an important lever if less need for energy is fully considered.

Difficult to assess but important are the costs of conservation and restoring of the environment and to assess a price for this collective and public good (bequest value)[185]. If the above-

[179] https://www.vectorenewables.com/en/media-en/blog/lcoh-how-is-the-price-of-green-hydrogen-calculated-1 03.02.23

[180] Tang, On et al. (2022) “Levelized cost of hydrogen for refueling stations with solar PV and wind in Sweden: On-grid or off-grid?, Energy (241) 122906

[181] OECD/IEA (2015) “Technology Roadmap - Hydrogen and Fuel Cells”

[182] European Commission – DG MOVE (2019) “Handbook on the external cost of transport”, V1.1

[183] It can be even upto 81% less for mountain roads such as Brenner compared to road

[184] (2023) „Entwicklung der Energieeffizienz des transitierenden Güterverkehrs am Brennerkorridor in Tirol” ÖBB (2023) 0.05 kWh per km per tonne on rail versus 0.19 kWh per km per tonne by diesel powered truck

[185] Carson, T. et al. (1999) “The Theory and Measurement of Passive-Use Value”, Bateman, I.J, and Kenneth, W.G. (ed.) “Valuing Environmental Preferences – Theory and practice of the Contingent Valuation Method in the US, EU and Developing Countries”

mentioned factors are considered for all alternatives and the full life cycle costs are taken into consideration, then the encompassing realistic levelled costs are achievable.

The importance to start incorporating external costs is to avoid overly simplified and from a holistic perspective wrong focus on one KPI such as energy efficiency as the only relevant criteria:

Bart Biebuyck (CEO of Clean Hydrogen Partnership):
*It is **not** about energy efficiency only. It is about climate efficiency. We have limited resources (renewables, time, money, humans, minerals) – that is why we do this (CO_2 -55% by 2030 etc.)*
Objectives:
⇨ *Offer best equation to get to the target!*
⇨ *Energy efficiency is equally important as time, money, mineral resources etc.*
*It is all about finding the right balance and that is what I call **climate efficiency**.*

The new energy system is likely to be more expensive in the beginning when the transformation needs to happen, but we must not forget that the old one is not (fully) pricing in the external effects and climate-related damages that it produces[186]. If we allow for a just calculation the GHG free energy and feedstock system will be cheaper, if all the following external effects do not have to be compensated or occur much less frequently:

- Costs of cleaning and re-establishing of the environment,
- GHG emission counteractions,
- climate change protection systems,
- rebuilding after extreme climate events,
- reallocation of millions of residents from

The list above is not meant to be comprehensive.

6.5 Rail transport sweet spot

In most academic and industry reports the transport challenges exclude rail transport of hydrogen as a viable option (see Figure 54). The sweet spot for rail transport can be twofold

a) **Import:** for smaller volumes (< 0.5 MtH_2/a) and distances of several thousand km pipelines are not yet cost-efficient. Specifically, if there is no pipeline that can be repurposed then land transport is more cost effective.

b) **Last mile:** if there is no pipeline, deep sea or barge supply within 200 to 600 km of distance to the customer then combined transport is in most cases a greener alternative that additionally reduces road congestion and does not add to the driver shortages in Europe.

[186] Warmbach, Achim (2022) "Klima muss sich lohnen" (English "climate protection must be worthwhile"), p. 156, Herder

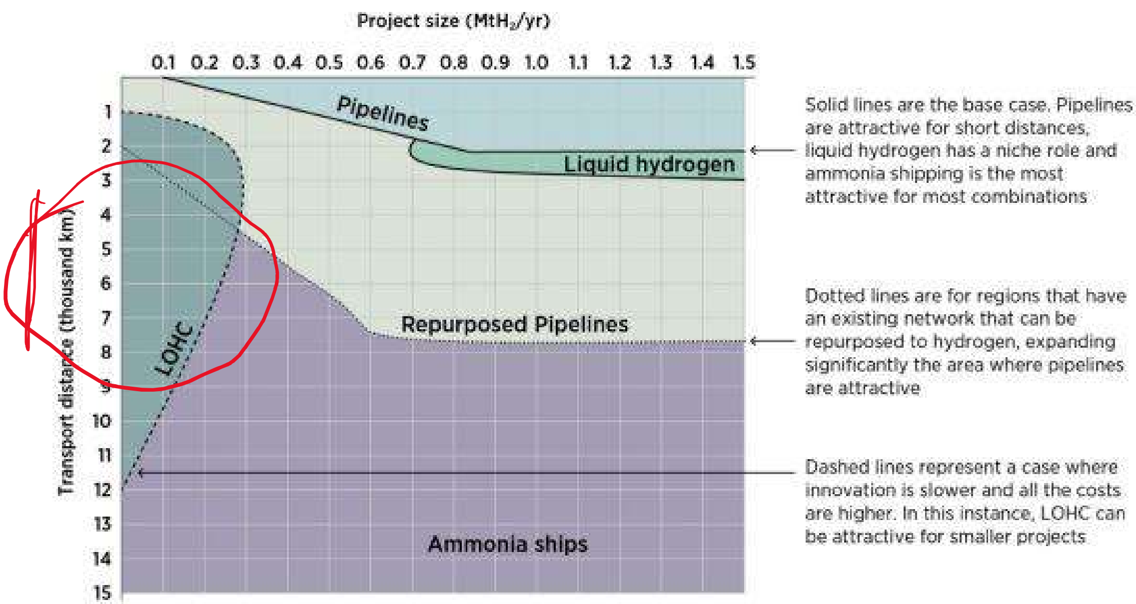

Figure 54: Volume vs transport distance[187]

A more complete overview requires the substitution of electricity transport via 380 kV twin overhead power lines against hydrogen pipelines. The latter have the advantage of receiving less public resistance and being able to transport up to 10 times more energy at less than 10% of the costs (of natural gas)[188]. For hydrogen the transported energy is about a third lower but due to the higher velocity the transport speed can be three times higher resulting in a roughly same advantageous cost-performance ratio (optimistic). The repurposing requires at minimum the investment into new turbines and the lifetime of the steel tubes will likely be lower due to an embrittlement effect. Other authors forecast higher pipeline costs for hydrogen than natural gas[189].

The rail sweet spot is in an area similar to the LOHC potential but can be extended to compressed hydrogen for the distribution of hydrogen to regions with decentralized demand. For the region of Central Asia the highlighted area is of relevance (see Figure 54). With combined road-rail transport smaller inland catchment areas are addressable. A train has the capacity between 50-150 tons of compressed hydrogen and therefore addresses a much smaller customers' demand. Ammonia trains have a capacity between 375- 450 tons. With the volume per container the supply of fuelling stations, decarbonising medium sized industry and other customers can be in focus if the distance to the ports or pipelines is more than 200 km.

Compared to the proposal of Husarek to drive from the coast to the South of Germany via road truck (see Figure 55) the attractiveness of combined transport increases with the distance to the sea. Realistically for some Northern regions pipelines will be available. However, for the Southern part of Germany the distances are well in the range where combined transport can be the better option from a decarbonise transport, security and resource consumption viewpoint.

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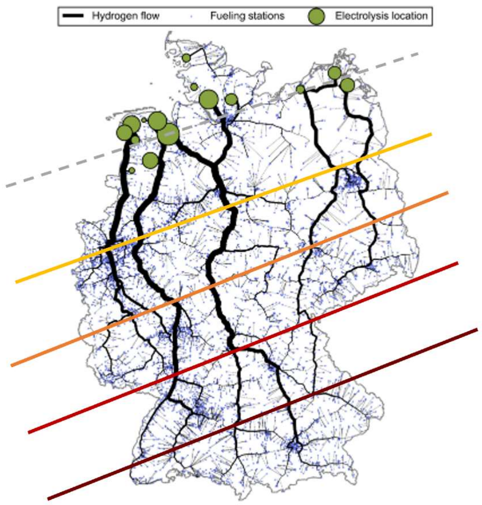
187 https://www.reutersevents.com/renewables/renewables/hydrogen-costs-hang-solving-transportation; IRENA (2022) "Global Hydrogen Trade to Meet the 1.5 Climate Goal, Part 1: Trade Outlook for 2050 and way forward"

188 Findlay, C. (2020) „What's your purpose? Reusing gas infrastructure for hydrogen transportation", Siemens Energy Magazine

189 Bossel, U and Eliasson, B. (2003) "Energy and the Hydrogen Economy", Alternative Fuels Data Center (AFDC) Report USA



Road-only scenarios for distribution to fuelling stations (see Husarek) need to be complemented by CT shipment options

A) avoid congestions on road

B) include additional volumes from central Asia

C) Reduce capacity constraints (loading road)

D) Reduce driver shortage etc.

Location	Distance	Road / Combined*
Duisburg	250km	Direct shipment / CT hub
Koblenz	450 km	Direct / Combined hub
Ludwigshafen	550 km	Combined transport central Asia
Regensburg	750 km	Combined transport central Asia

* Preliminary calculation results to be corroborated with more data

Figure 55: Tipping point of hydrogen from German shore (example)[190]

The likely scenario of shipping green hydrogen produced at the shore or delivered to the ports in the North sea or Baltic sea to the middle or south of Germany the distances can be considerable (up to 750 km) which is well in the range where combined transport can be not only less GHG intensive, more efficient than road (ICE or BEV), but also safer and less resource intensive compared to only relying on road. 1.3 million long range truck trips can be substituted by short road legs (max. 70 km) and approximately 13-29k trains[191]. For green hydrogen via CT there are two use cases that can be visualised in a simple matrix (see Figure 56).

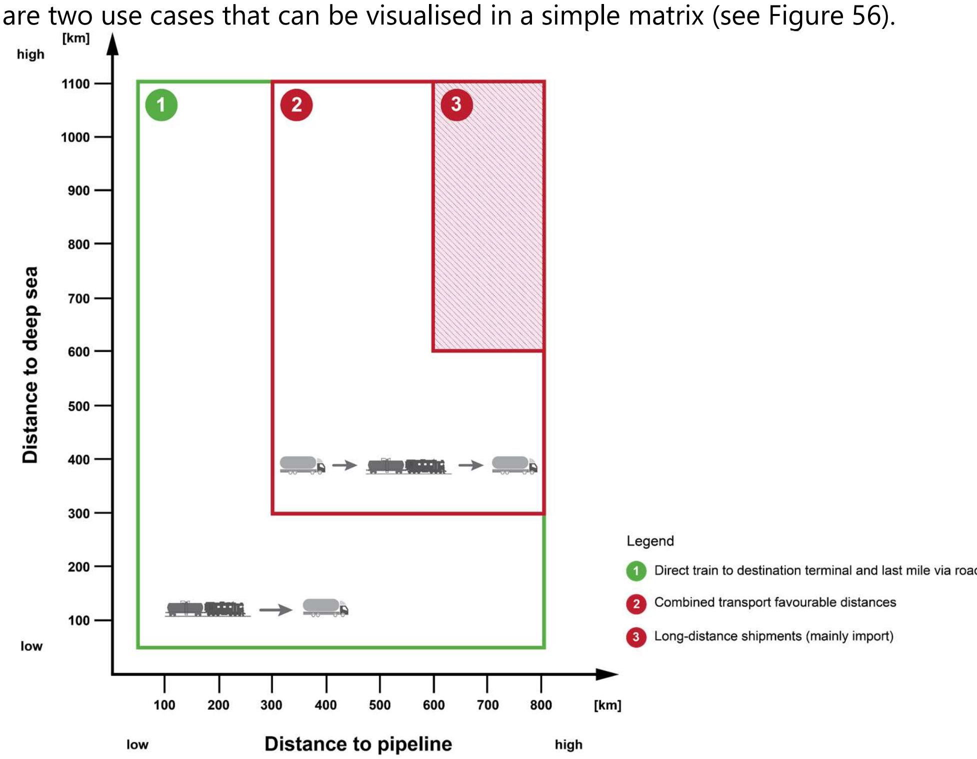


Figure 56: Hydrogen transport rationale (ambitious scenario)

[190] Husarek, D. et al. (2022) "Hydrogen supply chain scenarios for the decarbonisation of a German multi-modal energy system"

[191] Assumption is that about 2 Mto will be distributed in Germany from the shore to the South from 2035 or 2040 directly without a sufficient interconnected pipeline network available

(1) International transport from landlocked countries such as the example from Kazakhstan will be efficient up to 50-70 km close to the final customer destination if the starting point is already a rail transport (rail – road last mile)
(2) + (3) domestic transport between 300 km and most beneficial if more than 600 km distance could be delivered on rail. For the ranges between 200-300 km it needs to be analysed on a case by case basis.

The benefits for rail are assumed to be available if the rail programmes are being put in place as planned (see EU and UIRR rail study). If this is delayed or not fully implemented, then the benefits of a shift to rail might not be realised. If this is the case in 2030 onwards then the share of road shipments might even be bigger than today.

6.6 CO_2 pricing development

One decisive factor towards the carbon-zero transformation and the business ecosystem transformation to H_2 is the development of the CO_2 pricing. Without a price increase the cost of transformation will not be shared by those who still decide to rely on fossil fuels. Without a working CO_2 pricing the desired behavioural change is likely not to happen.

Current regulation in the EU foresees that the certificates of the Electronic Trading System for CO_2 emissions (ETS) will be reduced each year by 2.2% to 4.2% p.a. and the free CO_2 certificates will be eliminated by 2032. The trading of ETS is a relevant element for the energy transformation business models. It is planned to establish an ETS(II) for small enterprises and private persons but only enterprises will have to pay. This can lead to different prices for petrol depending on the fact that a corporate car driver needs to pay more than the private car driver[192]. The earnings of the new ETS(II) will be reinvested in the CO_2-free energy, transportation, and heating system for Europe. Only some exceptions for the chemical and steel industry will likely be allowed for exported products. For importers to EU there will be a CO_2 margin to pay. These measures will lead in theory to a level playing field in the EU but will increase the cost of living to finance the energy business ecosystem transformation where the energy required for transport (30%) and 30% share by hydrogen[193] is a large part of it.

If assumptions on CO_2 price development from 32 EUR (2021), 85 EUR today (to 100 EUR until 2030)[194] will materialize then the trading of CO_2 certificates can be a significant contribution to enable the transformation of hydrogen production, distribution, and consumption. A more comprehensive analysis by Bastien-Olvera and Moore calculates with a carbon price of 150 EUR[195] to be effective in 2020 that could have led to reach the 1.5°C goal.

There is a trend of some multi-national companies such as Nestle or Pepsi do carbon insetting, which is the investment in carbon reduction or removal projects on their own land or supply chain[196]. This process requires strict definition of when insetting is possible, its verifiable quantification, monitoring and global standard and methodology development. Similar to

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[192] See Christoph Herwartz (16.12.2022) "Das wichtigste Klimagesetz der Welt nähert sich der Fertigstellung", Handelsblatt

[193] Deloitte (2022) "Study on hydrogen in ports and industrial coastal areas", TRA Lisbon, 15.11.2022

[194] H2 book Quote? Or IEA (2022) "Northwest European Hydrogen Monitor"p.86 states 130 USD in 2030

[195] See Bastien-Olvera, B.A. and Moore, F.C. (2021) "Use and non-use value of nature and the social cost of carbon" Nature Sustainability, (4) p. 101-8; CO_2 price on 26.04.23 (https://ember-climate.org/data/data-tools/carbon-price-viewer/)

[196] Civillini, Matteo (2023) "Corporations push "insetting" as new offsetting but report claims it is even worse", ClimateChange

carbon offsetting there is critique of the current practices on its effectiveness[197] as double counting is possible (a company's own emission reduction should not allow to neutralise other emission sources).

German national CO2 pricing for road will develop from 25 EUR per tonne CO2 in 2021 to 55 EUR per to in 2025. The price increase of EUR 13 cent per litre petrol and EUR 15 cent per litre of diesel will result [198]. The EU pricing will be below that starting in 2027 with a ceiling of €45 per tonne by 2030[199].

6.7 Funding opportunities for future hydrogen business ecosystem development acceleration

Hydrogen is a central green energy and feedstock source and it is central part of European Green Deal and REPowerEU. The latter covers in 2023 additional allocations to Member States to support energy independency over three streams:

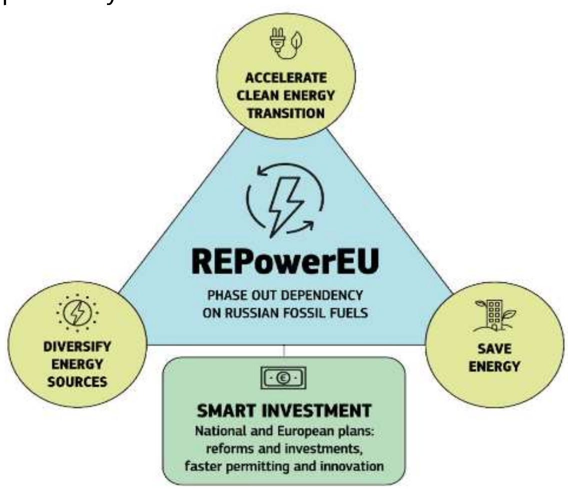

Figure 57: EU funding schema RePowerEU

Additionally, to this funding schema there is a large number of complementing sources for funds (see Figure 58):

#	Funding programme name	Link
1	Innovation Fund	https://climate.ec.europa.eu/eu-action/funding-climate-action/innovation-fund_en
2	Horizon Europe	https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en
3	Connecting Europe Facility (CEF) – Energy	https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/funding-guide/eu-programmes-funds/connecting-europe-facility-energy_en

[197] Guardian (2023) "Revealed: more than 90% of rainforest carbon offsets by biggest certifier are worthless, analysis shows"
[198] Schroten, A. et al. (2022) "Research for TRAN Committee – Pricing instruments on transport emissions", European Parliament, Policy Department for Structural and Cohesion Policies, Brussels
[199] https://www.euractiv.com/section/emissions-trading-scheme/news/eu-agrees-co2-tax-on-heating-and-transport-fuels-softened-by-new-social-climate-fund/

4	European Regional Development, Cohesion Fund, REACT-EU	https://ec.europa.eu/regional_policy/funding/react-eu_en
5	InvestEU	https://investeu.europa.eu/about-investeu_en
6	Just Transition Fund (JTF)	https://ec.europa.eu/regional_policy/funding/just-transition-fund_en
7	LIFE programme	https://cinea.ec.europa.eu/programmes/life_en
8	Modernisation Fund	https://modernisationfund.eu/
9	Recovery and Resilience Facility (RRF)	https://commission.europa.eu/business-economy-euro/economic-recovery/recovery-and-resilience-facility_en
10	EU-Catalyst Partnership	https://ec.europa.eu/commission/presscorner/detail/cs/qanda_21_5647
11	Clean Hydrogen Partnership	Several programmes, e.g. https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-jti-cleanh2-2023-05-01 [200]

Figure 58: Overview of EU hydrogen funding options

This is complemented by numerous member state initiatives and funding even on the federal state level (see example of Germany in ch. 2.3.3) Eventually selected by Member States (as is the case for the National Recovery and Resilience Plans)

6.8 Key take-aways from scenario analysis

The analysed Hyrasia One project has a valid requirement to use road-rail combined transport to move large volumes of hydrogen from Kazakhstan to Europe. Hyrasia One currently plans to use ammonia as available and more cost-efficient transport mode.

For customer groups that do not use ammonia directly the business case of hydrogen shipments might be possible if an end-to-end business case will be viable. This will depend on multiple improvements in the hydrogen business ecosystem:

(1) Rail infrastructure capacity build-up on the New Silk Roads (esp. Middle Corridor efforts must be expanded with the additional volume from hydrogen or hydrogen derivatives)
(2) Customers need to analyse their hydrogen sourcing and will need to engage in the hydrogen business ecosystem building to assure that they can receive hydrogen in the requested form and at competitive costs
(3) Funding or otherwise supporting road-rail implementation pilots to enable fast offering of the least GHG and least external effects producing land-based transportation mode
(4) Innovation in the cH_2 container area (cost reduction and capacity increase)

[200] The programme does not mention rail transport as an option. Further calls are planned and require monitoring (e.g. Small projects and new implementation 2024)

7 Pre-feasibility and proposal for CT hydrogen roadmap

7.1 Logistics service availability

7.1.1.1 Combined transport services

Combined transport operators (CTOs) organise the shipments via rail across the New Silk Roads on behalf of European and Chinese customers. Most the key operators are part of the Intercontinental Collaborative Platform (ICP) which elaborated the required development directions for the New Silk Roads condensed into an ICP Manifesto[201]. None of the CTOs have had experience with the shipment of pure hydrogen as gas or liquid in 2022 across one of the New Silk Roads or within Europe.

7.1.1.2 Operator View: DB Cargo BTT's Hydrogen Experience and Expectations

DB Cargo BTT GmbH is a subsidiary of DB Cargo AG and a logistics provider of cargo trains for EU-wide transports. BTTs key customer group are chemical and mineral oil companies for whom they mainly operate dangerous goods shipments. In addition, they own and operate terminals, own tank containers and manage rail cars. BTT is intensively preparing its readiness to ship hydrogen and hydrogen derivatives (ammonia, methanol, LOHC) since more than two years as the German hydrogen pipeline network will not be completed in the South of Germany before the 2040s. Even then not all areas will have direct access to hydrogen and rail is seen as a required alternative. Despite these general conditions no hydrogen shipment via rail has been performed in 2022 as the pilot train operations are supplied from an industrial side or via road, but BTT is already transporting high volumes of ammonia and methanol.

The main obstacle are the prices of the hydrogen containers that can contain about 1.25 tons of hydrogen at a cost of about 800 kEUR to 1 million euros. BTT is pursuing the optimisation in an R&D project to optimise the payload and increase the information availability (see Figure 59).

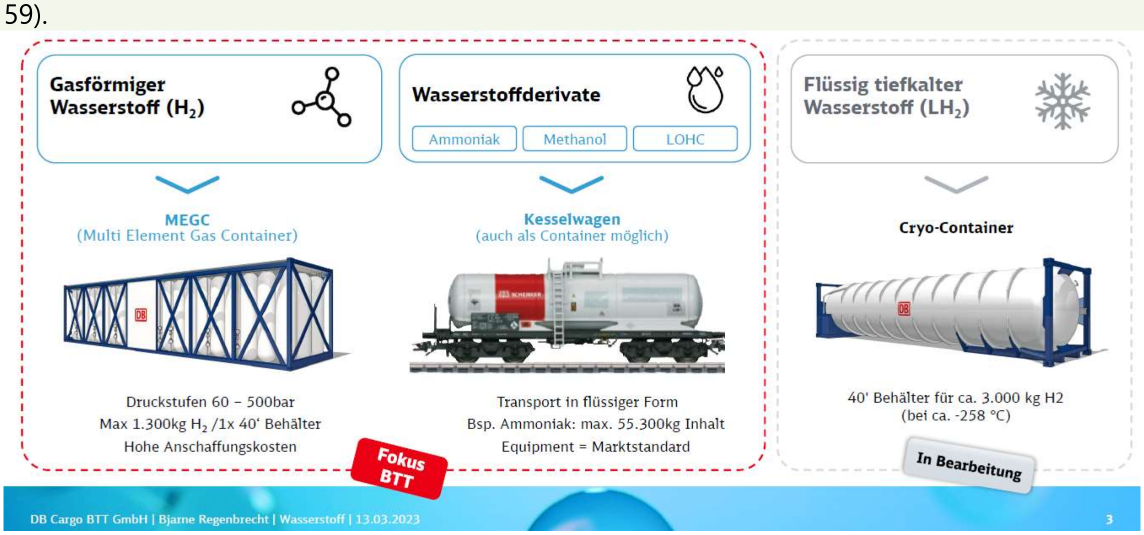

Figure 59: DB Cargo BTT's current focus for hydrogen transport covers three alternatives

[201] www.uirr.com to be published on 03.05.2023

The currently most favourable option for hydrogen related activities is to transport ammonia in rail cars with a payload of around 55 tons. Pressurised hydrogen, cryogenic liquefied hydrogen as well as LOHC are future options. One operative hurdle for pressurised hydrogen are filling times of 6-8 hours per container that require optimisation. A complete train container filling infrastructure at the production or hand-over site can be a solution. The topic of multiple purpose use of containers has been analysed but chemical and transport condition differences have been so far prohibitive.

7.2 Choice of feasible shipping scenarios from Central Asia to EU

For the purpose to establish the baseline for the pre-feasibility and roadmap development an initial market analysis was performed to identify the current solutions for shipments from a Central Asia (see Appendix 11.1: Central Asia hydrogen production project overview). The selection of the most promising and highest volume project lead to select the Hyrasia One project. The project location is distance-wise roughly in the middle between central China and Germany. Germany was chosen as the biggest net hydrogen importer of the EU as use case. For other EU countries the transport costs from Central Asia via rail will be higher (e.g. France) or lower (e.g. Austria, Hungary or Poland).

The successful implementation of the HYRASIA transport via rail will explore a so far less developed transport flow: From Central Asia to Europe and China instead of being mainly a transit country. Since the port of Kuryk is currently not capable of handling complete trains the substitute of the port of Aktau was required to receive realistic quotes[202]. The following scenarios have been evaluated (see Figure 60).

#	Scenario	From	To	Distance[203]	
1	KAZ-DEU (via Caspian)	Aktau	Duisburg	5290 km	http://ports.com/sea-route/port-of-aktau,kazakhstan/port-of-baku,azerbaijan/0.6 days at 20 knots
2	KAZ-DEU	Aktau	Ludwigshafen	5050 km	
3	KAZ-DEU (3)	Aktau	Schwarzheide	4950 km	If production capacity in Schwarzheide is below demand
4	KAZ-DEU (via Türkiye)	Aktau	Duisburg	7500 km	Demo pilot 2027
5	KAZ-DEU (via Brest)	Aktau	Duisburg	4800 km	
6	KAZ-DEU (via Caspian)	Aktau	Nuremberg	4350 km	

Figure 60: Possible routings from Central Asia (Kazakhstan) to Europe (Germany)

The options (1), (4), (5) and (6) were finally pursued and three different experienced combined transport operators were asked to provide price and transit time indications based on today's situation (between December 2022 to March 2023).

[202] The difference between Aktau and Kuryk is for this pre-analysis considered as not relevant since both ports will require a large infrastructure investment to cope with the expected volumes.

[203] Shortest distance assumed. Depending on chosen route distances can vary considerably.

7.2.1 Possible shipping scenarios from Kazakhstan

The following three routes from Kazakhstan were most promising[204]:

1) Aktau via Caspian and Black Sea to Duisburg or Nuernberg (Orange line)
2) Aktau via Russia and Türkiye to Duisburg (Pink line)
3) Aktau via Russia and Belarus to Duisburg (Green line)

Depending on the political situation options (2) and (3) can be subject to interruptions during the continuation of the Russia-Ukraine war.

Figure 61: Three Middle Corridor Silk Road paths

#	Leg	Transport mode (Alt-1)	Container type	Total Weight[1]
1	H2 production site	Rail (electrified) – 50 km	40ft, 500 bar	27 tons
2	Kuryk / Aktau (KAZ)-Alat (AZE)	Short sea (max. 250 TEU)		
3	Alat (AZE) – Poti (GEO)	Rail		
4	Poti (GEO)-Constanta (ROU)	Short sea (max. 250 TEU)		
5	Constanta (ROU)	Rail		
6	Budapest (HUN)	Rail		
7	Duisburg (DEU)	Rail		

Figure 62: Example of on optional requested path (in detail)

The transit time varies considerably between 33 and 19 days. This is too long for a distance of only 4350 km (Aktau to Nürnberg) or 7500 km (Aktau to Duisburg via Turkey) compared with the Northern Route, truck from Baku (10-11 days) or even sea shipments (Figure 63).

[204] Initially Kyruk was requested but for this port only single wagon traffic is possible therefore a switch to Aktau was required. The question which harbor will be expanded remains an open infrastructure question to be answered for this traffic.

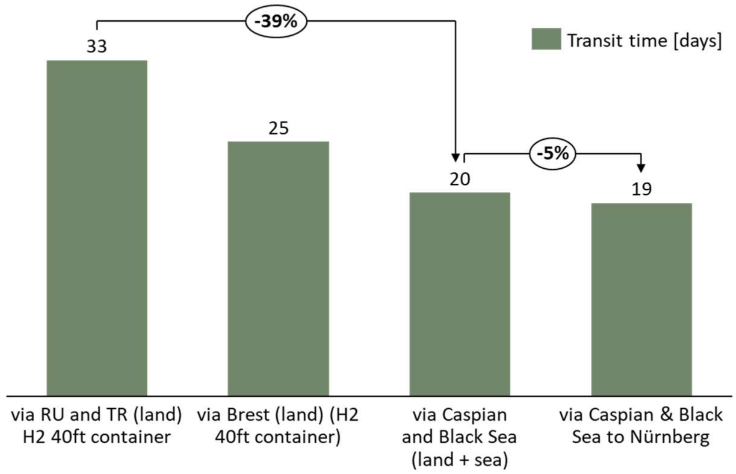

Figure 63: Transit time comparison of the four alternatives

7.2.2 Scenario 1: Shipment cost forecast from Kazakhstan to Germany (2030)

The current market price for grey hydrogen in the US is calculated at 5-9.5 USD with carbon capture[205]. The market price of hydrogen at the point of consumption is estimated at between 5,6 EUR and 6.79 EUR per kg hydrogen shipped from Northern Africa[206] to the shore or via pipeline for 2030.

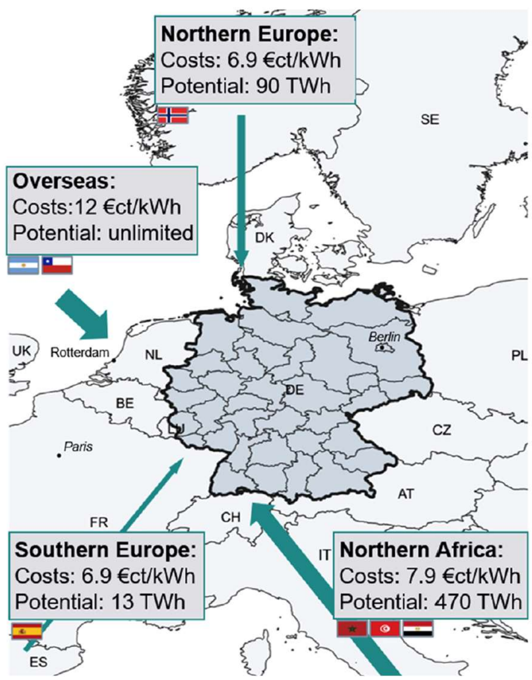

Figure 64: Import cost estimations for hydrogen[207]

[205] Brasher, Lance T. et al. (2022) "Growing Opportunities in Clean Hydrogen", Skadden Insights -September 22, 21.09.2022

[206] Unterlohner, Fedor (2020) "Comparison of hydrogen and battery electric trucks – Methodology and underlying assumptions, Transport & Environment, Brussels; Unterlohner, Fedor (2021) "How to decarbonize long-haul trucking in Germany – An analysis of available vehicle technologies and their associated costs, Transport & Environment, Brussels

[207] Husarek, Domenik et al. (2021) "Hydrogen supply chain scenarios for the decarbonisation of a German multi-modal energy system", Int. Journal of Hydrogen Energy (46) 3808-25

Statista calculates 3.95 EUR at port for 2030 via sea[208] whereas Fraunhofer estimates 2.6 EUR for green Hydrogen from Northern Africa without any conversion and last mile costs[209]. All of these prices do not include the transport to the final consumer. Customers with near-term hydrogen pipeline access are also excluded. Therefore, additional costs need to be assumed to compare localised costs. The green hydrogen price in the Duisburg catchment area is calculated at 8.85 EUR per kg[210] and was reduced to reflect current prices in Duisburg to 8.28-8.33 EUR per kg H_2 for the delivery to customer. Three different scenarios on the development trajectory of the required technology and transit times are applied to visualize possible futures in 2032 (see Figure 65). The prices are calculated on as-is transport costs and capacities to lay the baseline for the future development trajectory.

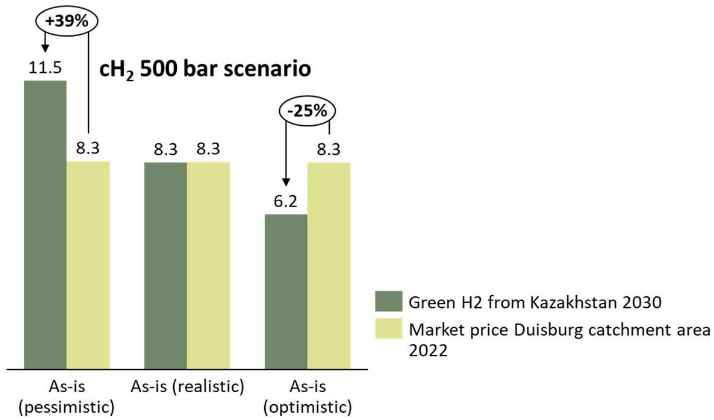

Figure 65: First price indication of hydrogen landed costs from Kazakhstan delivered to destination[211]

The assumptions underlying the scenarios are the following:

	Pessimistic	Realistic	Optimistic
Container capacity	No innovation	Small design improvement, cost down and innovation (13%)	Significant cost down, design improvement & innovation (26%)
Container costs	No cost reduction (low volumes)	Small cost down & innovation (13%)	Cost down & innovation (26%)
Cost of filling	No change	12.5% cost reduction	25% cost reduction
Transit time	No improvement (18-22 days)	Moderate improvement (13-15 days)	Major improvement (9-11 days)

Figure 66: Key assumptions for scenarios

208 https://www.statista.com/statistics/1220912/hydrogen-landed-costs-by-region/ at the ports in EU, US, and Japan

209 Husarek, Domenik et al. (2021) "Hydrogen supply chain scenarios for the decarbonisation of a German multi-modal energy system", Int. Journal of Hydrogen Energy (46) 3808-25

210 Lundblad, Therese et al. (2023)" Centralized and decentralized electrolysis-based hydrogen supply systems for road transportation – A modeling study of current and future costs" Intern. Journal of Hydrogen Energy (48) 12, 88.0223, p. 4830-44. Industrial use does not cover the cost of filling stations and the operational costs but includes the rough estimation of delivery costs to a customer within 50 km distance (incl. last mile delivery < 50 km). The new prices for the last leg were two local quotes.

211 Market price at Duisburg catchment area covers deliveries within the range of 70 km and a catchment area of about 13 mio inhabitants and several large industrial users. The prices do not include turnover or fuel taxes that might subject to change for green energy in this and the following charts.

Within the realistic scenario the prices for the landed costs would be competitive, if the other import options follow the forecasted trajectory. In the optimistic scenario the achievable prices almost reach a level that would allow the supply of filling stations for road mobility[212].

The cost of containers and shipping consume a large part of the total landed costs (between 66-68%) due to the long transit times today (between 20-34 days). One factor is however missing: the return of the container needs to be calculated as empty freight if a more conservative approach is applied. If the potential effects of road pricing, CO2-emissions and subsidises are included they compensate the price increase. This will be covered in the second scenario.

7.2.3 Scenario 2: Total shipment cost forecast scenarios from Kazakhstan (2030)

For the total landed cost view the return shipments need to be considered and the effects of CO2-pricing and initial ramp-up funding could be considered for 2030 and onwards. The three different routes are indicated with their different transit times and total cost levels.

	KAZ via Caspian & Black Sea to Duisburg area	*KAZ via Russia & Türkiye to Duisburg area*	*KAZ via Russia & Belarus to Duisburg area*
Transit time	20	33	25
Total transport costs [€] (incl. container return)	9.200	16.800	11.000

Figure 67: Key figures for the three different offered routes to the Duisburg catchment area (70 km)

The pricing was given under difficult conditions in Europe with many railway infrastructure works ongoing and still capacity constraints and pending infrastructure developments[213].

The additional costs of the return shipment make the business case for compressed hydrogen less attractive therefore other optimisation levers need to be considered:

1. More volume through more pressure (additional 28% more volume per container) for compressed hydrogen shipments
2. Initial support by institutional or state investors (e.g. EU Implementation program) to facilitate the ramp-up and industrialisation process (e.g. 60% of investment costs)
3. CO2 pricing increase by 2029 to be in place that can compensate parts of the logistics costs
4. Direct support for producers to lower the barriers and increase industrialisation speed

When the above-mentioned considerations are included the revised total landed costs for hydrogen are the following for the relationship from Kazakhstan to the Duisburg catchment area.

[212] Our own calculation estimates the break-even for economy cars at roughly the price of 6 EUR per kg hydrogen.

[213] Bilgic-Alpaslan (2022) "EU Study on Sustainable Transport Connections between Europe and Central Asia: Presentation of initial findings by the ERBD", European Bank for Reconstruction and Development, Brussels, 30.09.2022

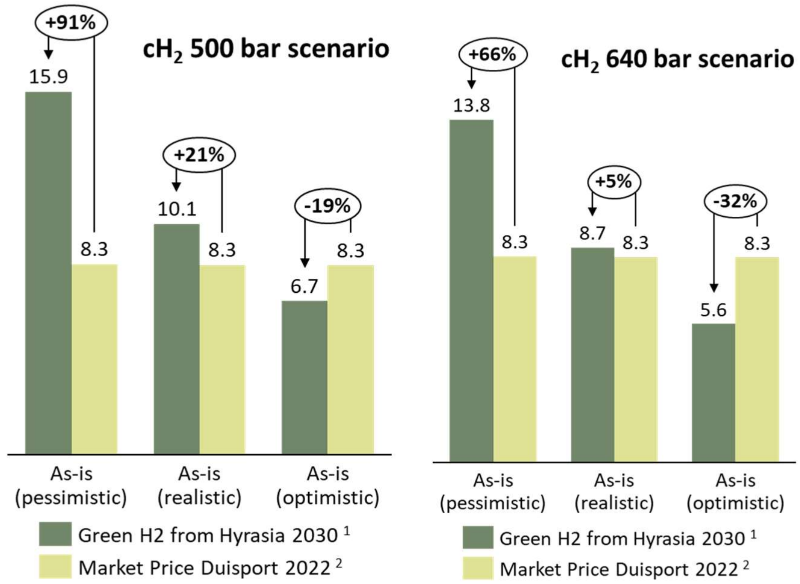

Figure 68: Total landed costs (incl. returns) from Kazakhstan for route via Brest (second best scenario)[214]

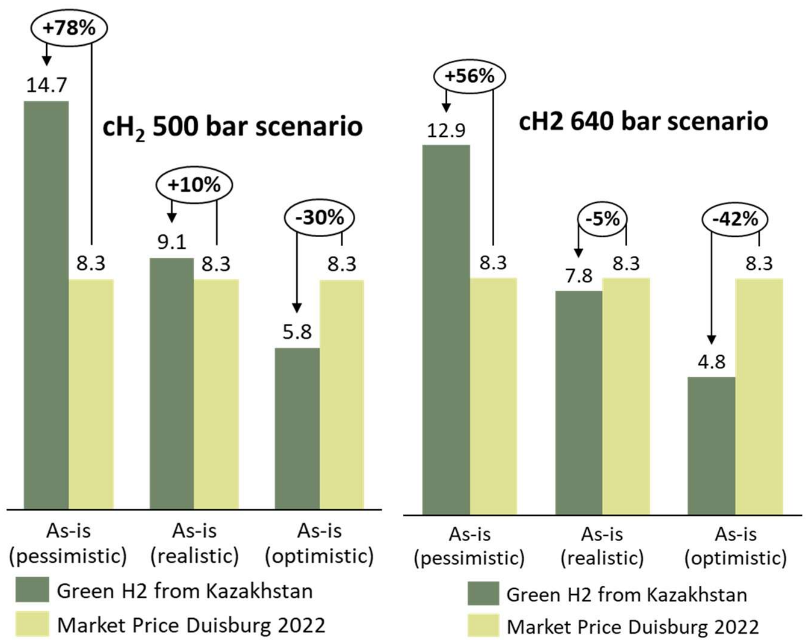

Figure 69: Total landed cost (incl. returns) from Kazakhstan for route via Caspian and Black Sea (best scenario)

Further optimisation can be achieved if the shipment will only be sent to Nuremberg (see Figure 70). The price level of about 5 EUR landed cost per kg hydrogen in the 640 bar scenario is competitive if the optimistic scenario conditions will materialise.

[214] Note: [1] own landed cost from Duisburg catchment area,
[2] Average cost from several sources for 2022 for Duisburg catchment area

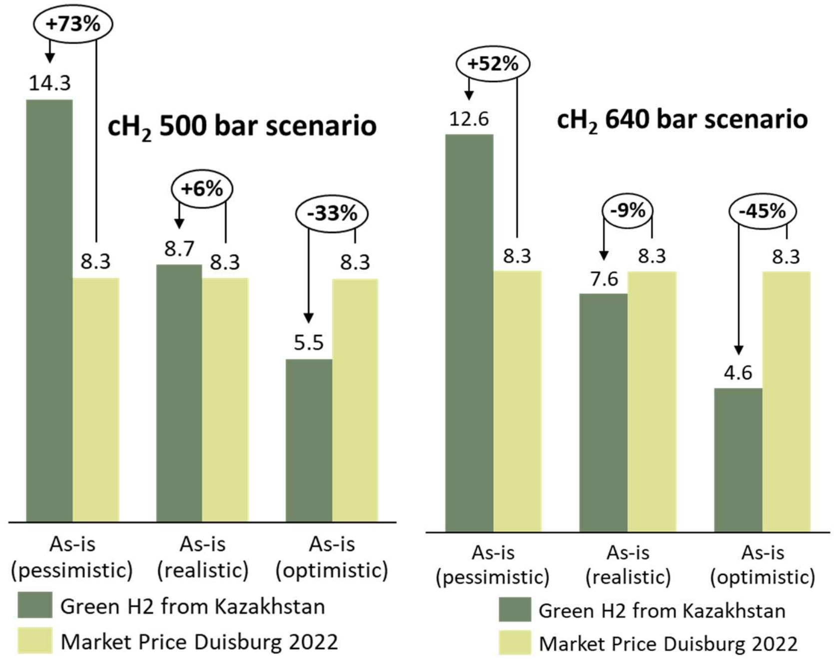

Figure 70: Landlocked customer location inkl. returns from Kazakhstan (e.g. Nuernberg catchment area)

Nuremberg is positioned 450 km further inland than Duisburg and its 50-70 km catchment area the costs are competitive with other hydrogen transport modes (except pipeline) and local grid produced hydrogen at minimum 8.3 EUR/kg (8.1 EUR plus shipping) in Germany (2021)[215]. For the optimistic scenario at 640 bar pressure, both road from coast and inland production and distribution can be more expensive from a total landed cost perspective than the supply via Kazakhstan.

If the hydrogen will only be shipped to Vienna or to Budapest transit times and costs factors can improve further. The indicative assessment highlights the need to enable the hydrogen business ecosystem transformation in the rail sector as current prices and services do not meet the requirements.

The price competitiveness with empty hydrogen container return shipments included, is far lower than forecasted prices for green hydrogen via pipeline or deep-sea ships. The analysis indicates that these prices will need to include all external effects to be on a level playing field. On top of this adaptation prices will differ considerably if hydrogen is shipped for a longer distance on an inland transport route from the closest harbour or pipeline access point. Additionally, the full costs of compression or liquification may need to be added. The correct comparable price for a location like Nürnberg needs to be calculated including the transport to the location.

The pricing for green ammonia is considerably more competitive (see Figure 71) on the assumption that the cracking of ammonia is so widely distributed that the extra transport leg, process costs and transit time extensions are insignificant.

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[215] Hydrogen Europe (2022)

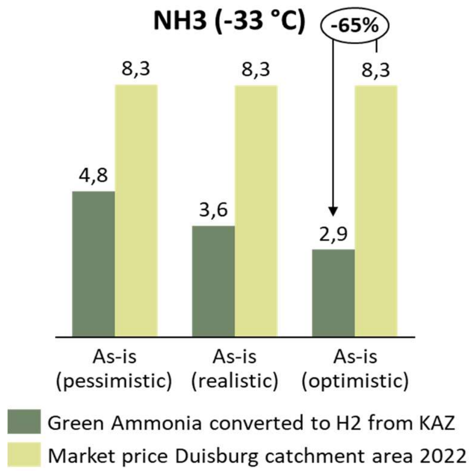


Figure 71: Green ammonia from Kazakhstan price estimations

The reconverted ammonia to hydrogen can become considerably more attractive if the CO2 savings are compensating part of the shipping costs. Without this compensation the prices are closer to the pure hydrogen price level in Germany. The uneven treatment of pure H2

7.3 Combined transport hydrogen pre-feasibility assessment

The analysis of the value chain, the gaps in business ecosystem for green hydrogen and the identification of one exemplary source in Central Asia lays the basis to make a first feasibility assessment of hydrogen and its derivatives as new business area for the road-rail transport stakeholders. The analysis was substantiated by interviews with key stakeholders and their assessment of their business potential and readiness. The purpose of this section is to determine whether a further exploration of combined transport as viable hydrogen transport option can be recommended. The next step would be to conduct one or multiple feasibility studies.

The chosen feasibility framework combines two sources:

1) We chose the successfully applied framework originating from IDEO's design thinking elements: desirability, feasibility, and viability (DFV) [216] framework that is also applied for business ecosystem feasibility assessments[217]. Usability complements the framework to stress the technical readiness as fourth-dimension. In essence the assessment focuses on the future road-rail hydrogen shipment services. It answers the questions if it adds value and is or will be usable, feasible and likely to find its customers in the next decades to come.
2) Pre-Feasibility Phase Blueprint methodology framework[218] that defines 6 steps for a pre-feasibility study for greening maritime shipping is similar to the chosen approach and was

[216] IDEO's well tested design thinking framework is used since the core of this pre-study is to evaluate if the continued innovation of hydrogen transports via combined transport are attractive for prospective end consumers and an initial estimation which volumes are likely (see https://makeiterate.com/ideos-desirability-viability-feasibility-framework-a-practical-guide/)

[217] Lewrick, Michael (2022) "Design Thinking for Business Growth: How to Design and Scale Business Models and Business Ecosystems", Wiley

[218] United Nations supported by the Rocky Mountain Institute launched the Green Hydrogen Catapult. Together with the Maersk Mc-Kinney Moeller Center for Zero Carbon Shipping the blueprint was produced Maersk Mc-Kinney Moeller Center et al.

adapted to rail: (1) Introduction, vision, and project setup, (2) Green hydrogen: Timing, capacity, emission and cost, (3) road-rail infrastructure, storage and fuelling requirements, (4) identification of trade routes, containers or tank wagons, and services, (5) policy, regulatory and funding, (6) pilot project selection framework, and (7) next steps

Usability is added to include the initial assessment of the current likelihood of customer acceptance for not yet existing services with technical, commercial, social acceptance, regulatory and business ecosystem challenges. The results of the interviews in combination with the gaps identified by the analysis of literature and own experience contribute to a strong need to evaluate the pre-feasibility. The results of the pre-feasibility study show a high need to pursue practical implementation projects further (see 9.3).

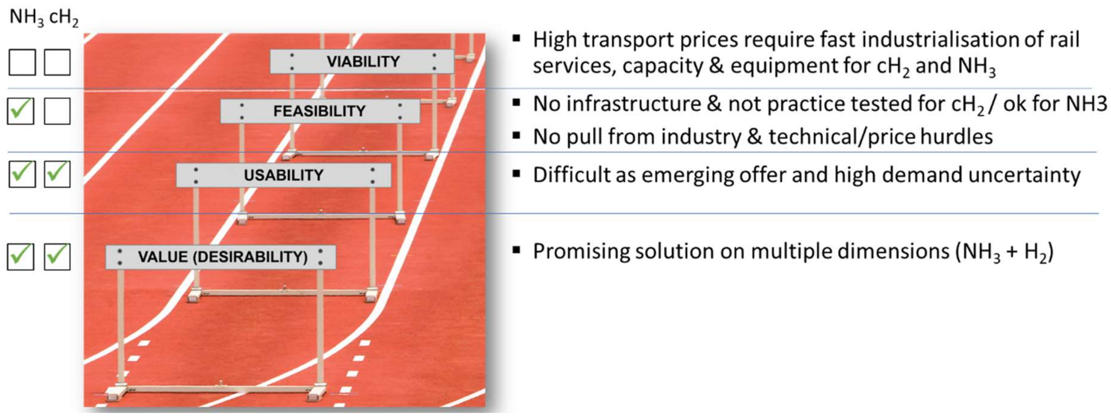


Figure 72: Simplified pre-feasibility assessment overview for hydrogen shipments from Central Asia to Germany

Assessment	Details	Maturity [219] [1-5]
1) **Value** (Desirability)	Hydrogen has rich application areas with a high contribution towards GHG avoidance and a high demand for Europe. If all application areas will follow the ambitious scenario, then import of hydrogen or derivatives will be required in many EU countries.	5 (Hydrogen) 5 (Ammonia)
2) **Usability**	For some applications green hydrogen is in its infancy (e.g. aviation or shipping), or it is in use on small scale (e.g. forklifts, trucks, cars) or green hydrogen can exchange grey or black hydrogen once the price level allow for or regulatory measures require it (e.g. steel production)	3-4 (Hydrogen) 5 (Ammonia)
3) **Pre-Feasibility**	The need to ship hydrogen via rail has been demonstrated in the trade lane from Kazakhstan to Germany. Currently only ammonia is pursued. Transportation of hydrogen is seemingly more expensive, but conversion infrastructure is missing and efficiency loss is high.	2 (Hydrogen) (Ammonia)
4) **Viability**	Commercial viability depends on the hydrogen derivative requested by customers. Ammonia is an established process on rail whereas transporting gaseous or liquid hydrogen as gas or liquid is not yet mature and tested.	2 (Hydrogen) 5 (Ammonia)

Figure 73: Pre-feasibility assessment summary of combined transport shipments for import and inland

(2023) "Green Corridors Guide to creating a Pre-Feasibility Phase Blueprint" https://cms.zerocarbonshipping.com/media/uploads/documents/Green-Corridors-Pre-Feasibility-Blueprint.pdf

[219] Maturity level scale starts with 1 = very low, 2= low, 3 = medium, 4 = high and 5 = industry standard

The conclusion is that for ammonia the need to offer these services is requested and it requires support to scale existing business to larger future volumes. Directly delivering H_2 to customers requires long-term planning to overcome the technical, cost and contractual hurdles to invest into this transportation, storage, and delivery mode.

However, with some targeted support and a business ecosystem or consortium approach the breakthrough seems currently not out of reach. The benefit of sharing the remaining risk of business case, technological or customer demand is that of a simpler supply chain, faster delivery and less energy loss, if cracking of ammonia can be avoided (approx. 20% of energy).

7.4 Roadmap for way forward until 2040 (ambitious scenario)

The description of the roadmap is elaborated only for the ambitious scenario[220]. The opportunities for combined transport to gain new capabilities, leverage existing experience in transporting energy and chemicals safely in an energy efficient way and with least impact on the environment are high.

7.4.1 Roadmap assumptions for Green H2 transports from Central Asia Business Ecosystem Transformation

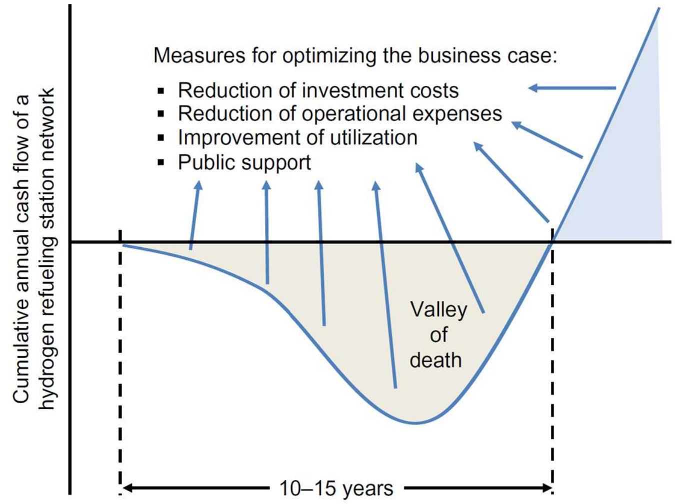
The following measures are assumed to be taken in due time:

1) Build all relevant infrastructure to scale up (esp. Middle Corridor of New Silk Roads)
2) Low risk of slow project and company decision making speeds despite long-term planning horizon and remaining uncertainty of the target in 2040
3) Trajectory based incentivization and build-up of capacity is performed from H_2 business ecosystem to match steep increase of hydrogen supply from 2026 to 2040
4) Increase of green energy share of 42.5% in 2030 will be reached [221]
5) Industrialisation of green energy generation, electrolysers, storage and transport technologies follows the expected development (technology push)
6) Pull from H_2 customers to decarbonise a wide spectrum of needs where hydrogen-based solutions are most suitable (e.g. transport, heat, power, feedstock)
7) Combined transport and other rail traffic is required to consume less fossil fuels and transport to the local end-consumer in land-locked regions
8) Ukrainian war situation will pertain from 2023 up to 2025 but will not escalate to other countries

If one applies the assessment of IEA from 2015 the break-even of **hydrogen refuelling** will materialize latest in 2030 (see Figure 74). With this event the local demand will increase considerably if in parallel the vehicles consumers increase (private and public transport).

[220] For the progressive scenario the impacts will be less in scale and delayed but will affect must stakeholders similarly.

[221] https://ec.europa.eu/commission/presscorner/detail/en/IP_23_2061



Valley of death in hydrogen deployment from IEA (2015).

Figure 74: Hydrogen refuelling will become cash-flow positive latest in 2030[222]

A similar development is to be expected for the hydrogen rail infrastructure including terminals, container equipment, rail-based fuelling stations or multi-modal filling stations that are in the process of planning, implementation, sign-off and ramp-up if these processes were started in time. For these long term changes the transformation plans require several years from planning to implementation and will require long-term thinking, partial investment support and in-time implementation.

7.4.2 Hydrogen CT business and public ecosystem building roadmap

The development of the rail-road hydrogen business ecosystem is a complex effort that requires a strong synchronisation of all actors. The figure below only highlights some key measures, but it is far from attempting a comprehensive overview (see Figure 75).

The roadmap describes the build-up of the infrastructure, services, standards and regulatory enablers for the import to the EU and road-rail transport with the EU. The supply chain for ammonia follows some of the same constraints (e.g. infrastructure capacity) without the technical and cost risks that liquid and gaseous hydrogen currently face. The roadmap focuses on the more complex and risky hydrogen shipments. However physical infrastructure, regulatory, interoperability, digitalisation and standardisation efforts need to be enhanced likewise in order to facilitate a shift-to-rail for hydrogen and its derivatives.

Phase1: H2 BE Pilot implementations (2023-2025)

The next steps are to identify, fund, and start implementation projects to reduce the uncertainty in the equipment design, regulatory and commercial conditions for the not yet feasible cH2 and lH2 shipments. These can be ideally small business ecosystems with R&D organisations and associations to facilitate the overcoming of potential challenges to elaborate standards and interoperability. Most likely, regulatory support for public funding from EU or national states is required to cover currently higher equipment costs and the standardisation efforts (e.g. equipment interoperability, alignment with other transport modes etc.). CO2 pricing and long-term H2 buying commitments plus transit time constraints (e.g. similar priorities such as

222 OECD/IEA (2015) "Technology Roadmap Hydrogen and Fuel Cells"

coal trains) will enable a more favourable pricing. In parallel, the stakeholders on the New Silk Roads (LSPs, CTOs, terminals, railway undertakings, and rail infrastructure providers) need to collaborate to align infrastructure build-up and standardisation and process digitalisation within the EU and across Central Asian states. Simultaneously, digitalisation and standardisation of commercial documents, customs documents and dangerous-goods declarations need to be performed to name only a few measures identified in the ICP manifesto. The implementation projects' learnings should be used to leverage the international standardisation and interoperability on the business ecosystem, legal, process, IT and asset level[223]. This effort will require a powerful and well networked set of experts that align with the existing associations and regulatory boards.

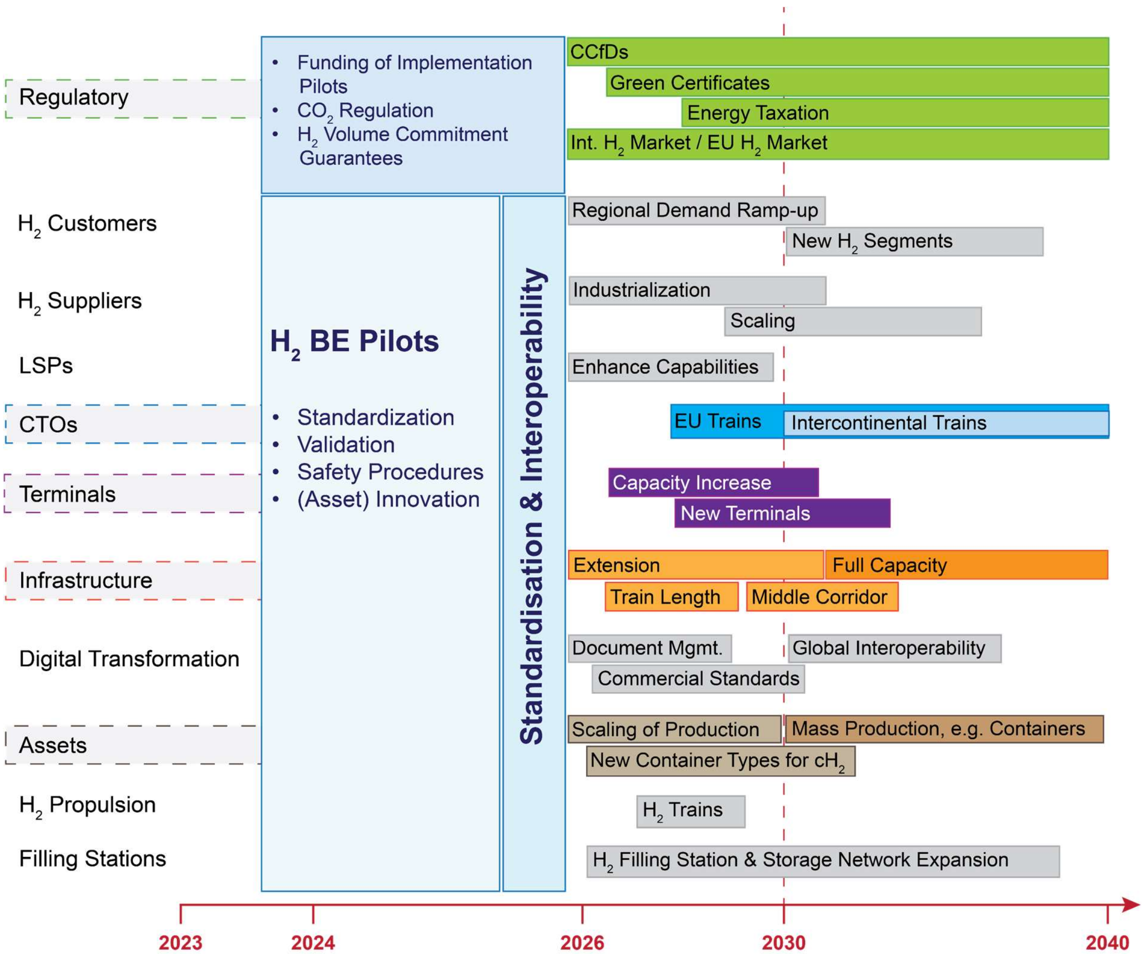


Figure 75: Combined Transport Hydrogen Roadmap

Phase 2: Ramp-up phase to establish relevant services (2026-2030)

The regulatory measurements that should be in place are CCfDs, Green certificates for H2, optimised energy taxation and an international and EU wide H2 market. Customers for hydrogen transports will with high probability emerge from 2026 onwards as the prices drop due to industrialisation successes from the electrolysers and other production component

[223] Nahir/Klueber (2020) developed an encompassing interoperability model which is update in a paper submitted to the G20 on global health interoperability. The model can also be applied to the logistics domain and is sector agnostic.

markets. In the second half the scaling of the producers of electrolysers[224] is likely to allow a faster growth of H2 production capacity. LSPs will advance in their offerings and processes to receive and ship hydrogen. CTOs will start to operate EU trains more frequently. Terminals will increase their capacity to handle longer trains and heavier containers or trailers. New terminals will increasingly build[225]. The terminal infrastructure will need to improve border crossings and connections with the New Silk Roads. Likewise, the extension of the electrification or carbon free propulsion will need to expand on the New Silk Roads and the capacity needs more than triple to cope with the expected increase due to shipments of hydrogen and its derivatives in 2030 and onwards.

The digital transformation of EU internal document management as well as international standards such as CIM/SGMS electronic consignment note will require further harmonisation and improved utilisation rates. Likewise dangerous goods and customs documents harmonisation will need to improve to reduce throughput times to make rail transport more attractive. The new assets (e.g. new container types for H_2) will be in the market that are improved in the dimensions of capacity, price and pressure to lower the cost by 40-60% by the end of 2030[226]. For shipments of ammonia, other hydrogen derivatives or other forms of transport (e.g. LOHC) the standardisation and interoperability issues are the same but some elements are already available. Especially the existing shipping practice lowers the barrier to expand service offerings.

For all of the measured indicated above only execution and implementation phases are listed. Planning must often start 2-3 years in advance (sometimes even longer to include BE and consortium building, feasibility studies and standardisation processes).

Finally, hydrogen propelled trains will increase with lower hydrogen prices and in parallel improved hydrogen refuelling station (HRS) networks (e.g. minimum each 200 km on TEN-T network)[227].

Phase 3: Scaling of hydrogen volume and customers (2030-2040).
New customer groups for green hydrogen from the airfreight and seafreight area will be emerging with new challenges on the delivery (locations, volumes, service levels). This must be matched by an increase of hydrogen supply and distribution capabilities for local, regional and global production. The CTOs can start organising more and more intercontinental hydrogen trains to meet the EU demand. The terminal and rail infrastructure must be prepared to cope with the additional volume. Especially the Middle Corridor needs to be able to handle 5 to 50 times of today's volume depending on the availability of other routes and the hydrogen capacity shipped in one unit. This massive increase can only be possible if also the throughput time via harmonised processes and interoperable digital solutions are in parallel put in place. Finally, on the end consumer side the network of fuelling stations and hydrogen storage facilities will generate more transport needs.

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[224] Applies to Proton Exchange Membrane (PEM), Anion Exchange Membrane (AEM), Alkaline (AEL) or solid oxide electrolyser cells (SOEC)

[225] D-fine (2022) "Roadmap to Zero-Carbon Combined Transport 2050"

[226] The manufacturer NPROXX announced at the Hannover Fair in 2023 an improvement by 40% already in the near future

[227] https://ec.europa.eu/commission/presscorner/detail/en/IP_23_1867 AFIR

The regulatory environment must set the conditions that the public & business ecosystem building will increase its momentum to limit the chicken and egg situation that we experienced in many interviews. It is mission critical to overcome this chicken-and-egg situation fast to allow for sufficient time to develop the mass production capabilities and the learning curves and open innovation generating results to drive costs down.

Customers need convincing arguments to bet early onto the forecasted hydrogen prices to materialise and need to start changing their feedstock in pilot projects to drive real early demand. The required energy transformation will need private and public funding, courage, motivation and sound long-term business planning to be successful.

7.5 Core hydrogen transport BE transformation recommendations

7.5.1 Electric and Hydrogen ecosystem coexistence required

The greening of energy supply purely by betting on battery-based transport will not be possible due to the energy grids not ready for peak demands nor the network for charging is likely to be available in Europe or the US with the required density [228]. One truck stop for electric trucks is estimated to require the energy of a city of 10’000 inhabitants and even more extreme scenarios are thinkable if the holiday seasons in Europe start.

Worst Case Scenario: If the holiday season starts in France in August and 100’000 BEVs want to be charged in Lyon, then this infrastructure cannot be set-up economically and ecologically for peak times nor are space and power supply available or the grid infrastructure is realistically built. One could argue it requires a change of behaviour, but the political costs are high too.

Many more arguments can be cited like the dependence on rare metals, projected lithium scarcity etc. that require to develop an H2 infrastructure in parallel to avoid the risk of systemic undersupply of energy, electricity, mobility and heat or political dependency on a few countries.

For the transport sector a slight dominance of hydrogen towards other green energy forms is even expected by Cerniauskas et al. for the German market[229].

Passenger vehicles	Buses	Trucks	Rail transport	Shipping
50%	60%	50%	75%	75%

Figure 76: Assumed hydrogen transport penetration rates for Germany in 2050 (medium scenario)

Synfuel might be a required bridging solution to allow for an economically feasible transition to hydrogen and electric-based road transport and a greening of rail for the time where the supply of green fuels and electricity are not possible in all regions.

[228] Tom Randall (2022) “Electric Truck Stops Will Need as Much Power as a Small Town” (2022), Bloomberg https://www.bloomberg.com/news/articles/2022-11-14/tesla-s-electric-semis-are-coming-and-trucks-stops-aren-t-ready

[229] Cerniauskas, S (2019) “Future Hydrogen Markets for Transportation and Industry – The impact of CO2 Taxes”, energies (12) The break-down to each EU country was not performed in this pre-study, but the example of Germany as one representative of a large EU country substantiates the argument sufficiently.

Unrealistic single solution panaceas (e.g. only electrified trucks or cars) increase prices and will reduce the resilience in case of shortages (e.g. loading infrastructure, energy capacity in the grid or rare earth metals). The theoretical cost-efficient solution might not fit for all contexts and might also be a highly risky one. Therefore, a resilient strategy is to foster alternatives in parallel. This way the strengths of each technology can find its optimal use case and context.

7.5.2 Interoperability of Multi-Modal Hydrogen Transport

EU activities are planned in the hydrogen strategy[230] and in alignment with further countries in the Clean Energy Ministerial Hydrogen initiative (CEM H2I) to produce an interoperable hydrogen economy. This objective was supported by all interviewees from the supply chain as critical objective to be achieved.

At minimum the following other stakeholder are to be involved:

1) UN-ECE
2) International Maritime Organisation to cover the import via deep sea,
3) Rail and combined transport associations and agencies (UIRR, UIC, ERA)
4) Harmonisation of automotive regulation for hydrogen vehicles.
5) TEN-T networks (Road, Rail, waterways, Pipelines)
6) Cooperation under G20
7) International Energy Agency (IEA) and the
8) International Renewable Energy Agency (IRENA),

Early exchange on the forming of a business and public hydrogen ecosystems creates further opportunities for exchange of experiences and best practices if it is not only confined to the EU geographic region but encompasses the Central Asian and Asian countries.

This report shows that many of the actors have not yet started to develop their strategy or execute it in line with the future transformation towards a low-to-zero-carbon and hydrogen as well as battery-based business ecosystem. The focus here was only to explore the connection with possible import sources from Central Asia. The complete picture must include the sea ports, inland ports, and the development of the end-to-end standards and their interoperability. Sector specific choices may lead to higher than needed cost levels and longer time spans where actors are not planning their first steps to embrace hydrogen and its derivatives fully. If this chicken-and-egg hurdle will not be overcome in the next 1-2 years, the European multi-modal supply chain including road-rail will not be ready to offer the most versatile and cost-efficient services to customers that need to be accessible at competitive prices to decarbonise their transport service to avoid CO_2 taxes and ETS penalties.

[230] European Commission (2020) "COM(2020) 301 final – A hydrogen strategy for a climate-neutral Europe" in alignment with Mission Innovation and the Clean Energy Ministerial Hydrogen initiative (CEM H2I)

Security of supply inter alia through interoperability, secure and reliable system operation and transmission of hydrogen to major demand centres and storage sites which ports will be is a prerequisite to develop supply chains.

To ensure that the different greening and energy transition pathways for ports do not get stuck in a discussion about the chicken-and-egg dilemma, coalitions or framework agreements should be developed by key stakeholders. Such coalitions could initially involve shipping lines, port managing bodies and energy providers at port level and could in a later stage evolve into a deeper cooperation with connecting ports. Such a bottom-up approach would see an individual port engage key stakeholders based on the port's individual roadmap, which provides a detailed plan of pathways for the greening of the shipping and takes into account each port's particular circumstances. The roadmap should be accompanied by a timeline which engages all relevant stakeholders: the port, the shipping lines, the energy sector (producers and providers), and other European ports where suitable.

Figure 77: Sea shipments strategy for hydrogen shipments via the Port of Rotterdam[231]

7.5.3 Support of Business Ecosystem building via multi-stakeholder engagement

Incentivise and support initiatives that foster interoperability and a multi-stakeholder approach throughout the wholes supply chain must be provided by regulators. Otherwise, the business ecosystem transformation towards a decarbonised EU business and private power, transport, heating and electricity system will develop only too slow.

The chicken and egg problem must be avoided to prevent from a downward spiral risk of a vicious circle and many stranded assets that have been build or are in construction.

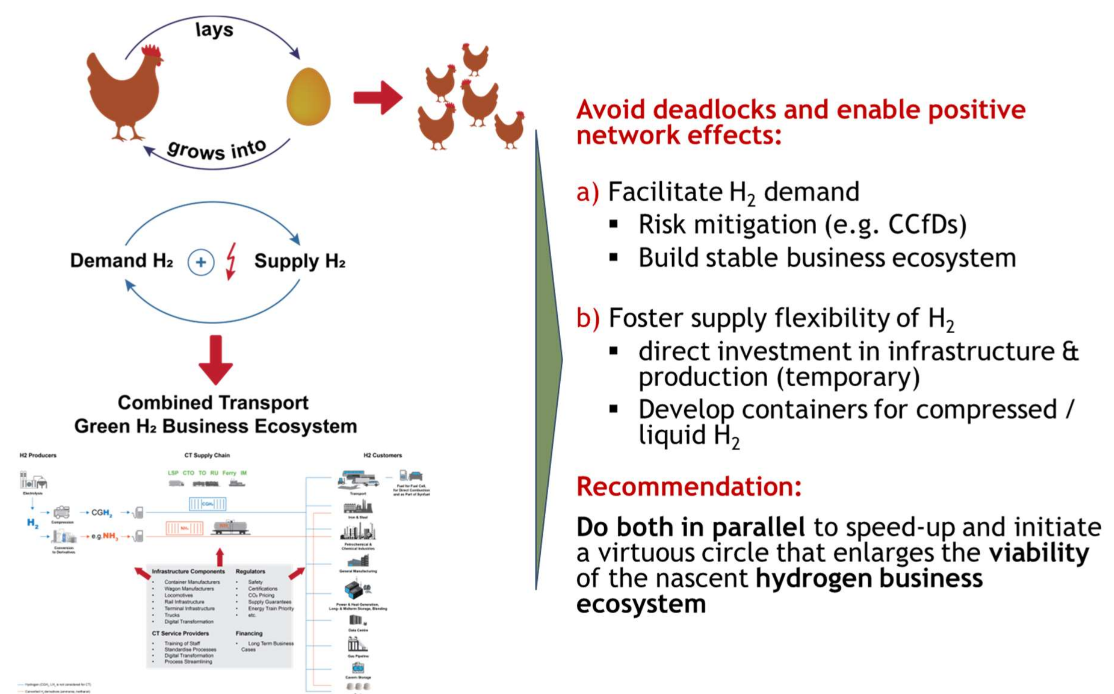

Figure 78: Recommendation to push the Hydrogen Business Ecosystem Development

[231] Hydrogen Europe (2021) "How hydrogen can help decarbonise the maritime sector"

There is a thin line between competition law and business ecosystems but the design and regulation of it can make a difference[232]. Therefore, we recommend private-public business ecosystems to foster local hydrogen networks in extension to hydrogen valleys for a faster availability of the public good resilient and affordable energy supply. If required, some countries (e.g. Germany) can have ministerial directives to allow even mergers and override the competition law conflict if there is a higher public value to be expected.

7.5.4 Start now: No regret moves

Pilot systems to prove H2 transport via rail according to customer need scenarios are the consequential follow-up of a promising pre-feasibility study. The following paths can be explored sequentially or ideally in parallel:

A. H2 direct consumption and shipment of cH2 for a selected customer target group
B. H2 direct consumption and shipment of lH2 for a selected customer target group
C. Energy transformation for ammonia form small sizes

This procedure will generate the following benefits to enable a robust and plannable CT offering for hydrogen and its derivatives:

1) Enable learning curves
2) Identify issues and regulatory gaps for roll-out
3) Clearer business cases based on effective cost-benefit-risk assumptions
4) Identification of the R&D gaps and close monitoring of the progress rates

Enable the development of multiple sources of green energy for transportation and transporting different forms of green energy. We recommend to set favorable conditions to allow for the development of batteries, hydrogen, ammonia and other ways of transport as the one fits-all optimal solution will likely not exist. There are some promising developments that could improve the efficiency or capacity of both the transportation of energy vectors as well as the energy supply for propulsion. Currently too early to decide where innovation will be progressing most in the next 5-10 years. Based on our initial findings hydrogen shipments via rail from some sources can become competitive, are required from a resilience viewpoint etc.

Pre-requisites to foster green energy transformation with hydrogen can be based on the following assumptions to increase the success potential:

1) Multiple sources of clean energy
2) All external effects – no limitation to a dysfunctional KPI such as energy efficiency but include prices for raw materials and
3) Political resilience
4) Logistics concept resilience (as demonstrated on the solidarity lanes)
5) Continued and extended close collaboration with neighbouring countries such as the countries Middle Corridor countries to enable better trade and logistics context for the EU and the Central Asian countries

[232] Wambach, Achim (2022) "Klima muss sich lohnen: Ökonomische Vernunft für ein gutes Gewissen", Herder

7.6 Key take ways from pre-feasibility and roadmapping

The interviews and the low rate of projects started yet is an indicator of the high uncertainty when and at which price hydrogen can be available and where. The business cases are not yet always convincing and the **chicken and egg** situation (ch. 7.5.3) is currently stopping the push for sector and country overarching potential realisation.

On the other side there is still some technological development and industrialisation required to reach the desired price levels (e.g. electroysers, green energy availability, optimised hydrogen container designs) that will take 1-3 years.

Some companies are exploring their product capabilities further and there are developments in many dimensions as we have seen in the interviews. Green hydrogen as new energy and feedstock source is attractive and there is sufficient demand to secure return on investment into the preparation for combined transport.

The public and business ecosystem affected by the transformation is depicted in Figure 79. Since the some parameters and manufacturers are new, the transport conditions are not yet fully defined and the capacity in the supply chain is not there yet, the transformation task is large.

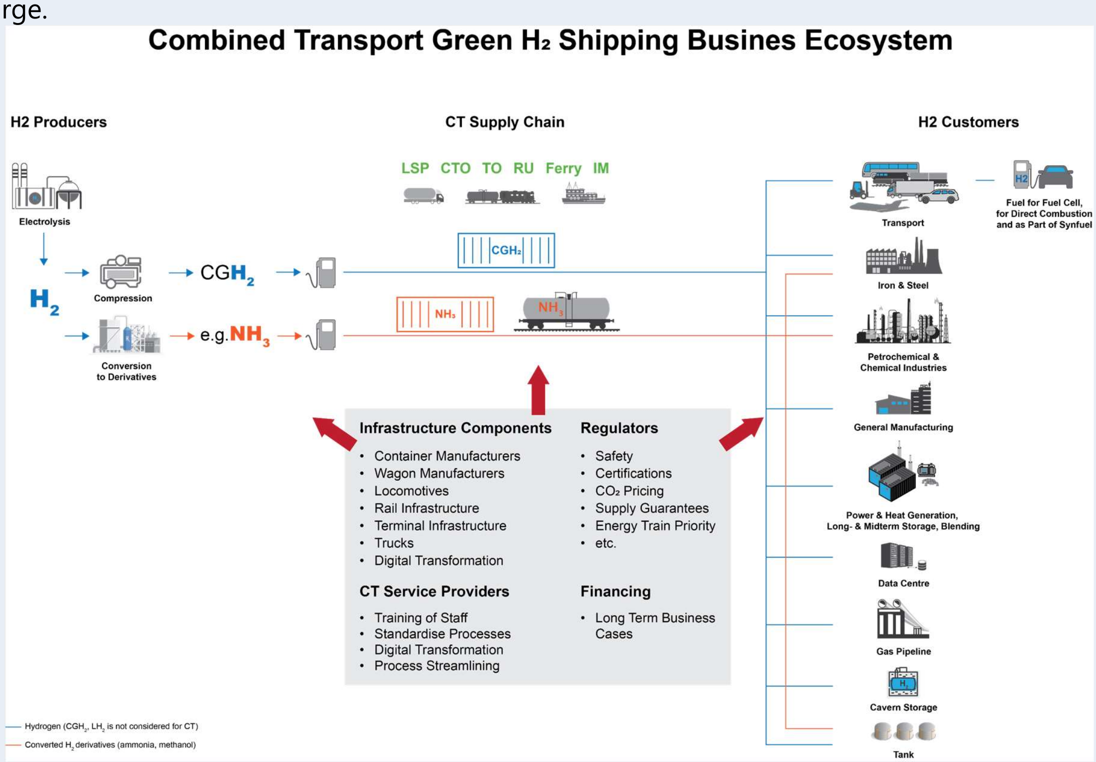

Figure 79: Hydrogen Business Ecosystem Change needs

The proposed way of accelerating alignment is to connect the relevant players to achieve the best interoperability on all levels that is possible by early alignment of motivation, business needs, gaps and capabilities.

8 Stakeholder recommendations for H_2 business ecosystem development

Only 4% of projects that have been thus far announced are under construction or have taken a final investment decision. Uncertainty about future demand, the lack of infrastructure available to deliver hydrogen to end users and the lack of clarity in regulatory frameworks and certification schemes are preventing project developers from taking firm decisions on investment.[233]

On the contrary the identified potential volumes are high and require a concerted effort to enable an additional volume for rail of minimum 200k to 400k TEU only for the import relation from Central Asia. The increase at some infrastructure locations will be more than ten times the volume that is handled today. The opportunity to open this volume for rail also brings some challenges and the opportunity to green rail freight on the New Silk Roads to reduce the CO_2 and GHG effects.

8.1 Regulatory and policy enablers for H_2 business ecosystems growth

8.1.1 Carbon pricing for all modes

EU initiative to revise the ETS to price all transport modes until latest 2030 by extending it to maritime, road and buildings is important to price-in environmental and health impact of the carbon economy. The funds are used to finance the transformation into a carbon-free and GHG-fee worldwide future. The planned import duties of the Carbon Border Adjustment Mechanism (CBAM) may be in conflict with free trade but may not be avoidable to protect EU's economy from less balanced competition.

8.1.2 Carbon Contracts for Difference

As a complement to carbon pricing the EU has developed an instrument to foster the green and hydrogen business ecosystem transformation that is called Carbon Contracts for Difference (CCfDs). It aims to accelerate investments to achieve the deployment of breakthrough carbon-free technologies by de-risking the CO2 price volatility[234].

BASF's Senior Energy and Climate Policy Manager claims that
"CCfDs do have the potential to make these technologies and others market ready. CCfDs can really help to bridge this gap, to offer products to markets, develop these markets, and to de-risk these processes."[235]

The benefit of this instrument is that private companies and states can bridge the transition phases by entering a risk sharing contract. This is an important element to enable the transition.

233 IEA (2023) "Towards hydrogen definitions based on their emissions intensity", https://www.iea.org/reports/towards-hydrogen-definitions-based-on-their-emissions-intensity

234 https://www.ewi.uni-koeln.de/en/news/carbon-contracts-for-differences-ewi-team-shows-opportunities-and-risks/

235 https://cefic.org/media-corner/newsroom/carbon-contracts-for-difference-the-urgent-boost-needed-to-deploy-breakthrough-green-deal-technologies/

8.1.3 Direct investment and implementation pilot funding

Despite the promising outlook financing green technology, industrialisation or capacity build-up is still a major hurdle despite many national or EU incentives. Without the availability of direct funding to perform CAPEX/OPEX investments larger than 10 million Euro large scale transformation will not happen in an accelerated speed or may move to other regions of the world.

8.1.4 Green hydrogen definition and certification

The green hydrogen definition of the EU and its certification process are valid to foster the decarbonisation. The risk of a too strict definition is that too strict boundaries may curb relevant initiatives or adoption processes towards achieving the decarbonisation targets.

8.1.5 Scrutinise national regulations curbing hydrogen ecosystem building

German regulation on profit skimming can stop previously promising hydrogen projects (e.g. Wunsiedeln) if the internal electricity price is subject to excess charge based on turnover values. Similarly, biogas and the stopping of green energy production are deficits in need of correction in order to achieve the utmost impact without more investment.

8.1.6 Customs and commercial rail documents harmonisation acceleration

The import of hydrogen via rail requires a strong process improvements and standardisation to allow a higher degree of interoperability. Planet LL2 has collected the hurdles, requirements and demonstrated a set of recommendations to overcome the delays and achieve a level playingfield[236].

8.1.7 Infrastructure build-up throughout all production and distribution phases

1. Foster resilience and alternative transport paths (as green as possible)
2. Funding of pilot projects and long-term investment stability for companies to build a hydrogen or hydrogen derivative based road-rail infrastructure and clarification of operational risks
3. Alignment of initiatives to contain costs (sector coupling)
4. Foster parallel investment in other elements to store and transport hydrogen to enable a parallel change towards a hydrogen public-business ecosystem that is cost-efficient and more resilient towards disruptions and change of supply sources.
5. Realistic point of consumption transportation costs to compare the costs including the last mile transport costs
6. Cross-fertilization from developments for the road-mobility in terms of filling station and storage capacity and costing effects[237]
7. Infrastructure building and acceptance hurdles must be addressed[238]

Risks: Monitor progress in gas pipeline conversion projects and network extensions. Still medium sized industry consumers, logistics industry and smaller private consumers remain

[236] UIRR/IBS Intercontinental Collaborative Platform (2023) "Manifesto on New Silk Road Development: Recommendations to overcome critical hurdles for Combined Transport Services", presented on 03.05.2023

[237] Böhm, Mathias (2022) "Review and comparison of worldwide hydrogen activities in the rail sector with special focus on onboard storage and refueling technologies", Int. J. of Hydrogen Energy (47) 38003-17

[238] acatech, DECHEMA (eds.) (2022) „Auf dem Weg in die Wasserstoffwirtschaft - Resultate der Stakeholder*innen-Befragung"

markets for combined transport-based shipments of larger volumes. Since the costs of retrofitting existing pipelines is only at 10-15% of rebuilding costs the conversion and use of existing pipelines is realistic. The blind spots and the seasonal storage-based business model remain attractive for rail-based transport. Secondly, the resilience aspect of securing the possibility to guarantee import of energy via combined transport is a relevant aspect to be considered by governments. The gas price increase in 2022 has shown that price increases can overcompensate the multi-channel sourcing costs (deep sea shipping, pipeline, rail and road transport costs). Additionally, CO_2 price increase will change economics towards more favourable combined transport relations.

8.2 Inter-association collaboration on the New Silk Roads

The collaboration between associations to improve the situation has been started with the Intercontinental Collaborative Platform (IPC). For the preparation of the hydrogen business and public ecosystem transformation effort additional stakeholders need to be involved. In this study the involvement of the TITR association for the Middle Corridor and several EU institutions is a starting point but not sufficient. As indicated above the financing side and additional stakeholders such as shipper associations and the hydrogen consumers can be relevant participants plus the national regulators to shape the future of the New Silk Roads for a more seamless and economically feasible rail-road hydrogen supply to Europe.

8.3 Demand and supply

The hydrogen supply chain requires to be robust and resilient to be able to compensate unplanned major disruptions (e.g. pandemics, wars, attacks on pipelines). The multi-modal hydrogen transport system to link local and international demand and supply needs combined rail to reach a high flexibility and robustness.

We have shown that shipments from Central Asia can be competitive if the infrastructure and service offerings are improved but in order to enable this carbon-low transport mode several activities need to be pursued until 2030:

1) Detailed break-down of customer group demand profile and transport mode matching
2) Secure and proven shipment via rail of cH_2, Ammonia and lH_2 need to be performed in practice to enable a sound decision basis for the further build-up of the hydrogen road-rail public-private ecosystem

8.4 Infrastructure providers

8.4.1 H_2 infrastructure development

Standardisation is required to increase the consumer conversion capabilities to satisfy decentralised demands of transport, power supply and heating. Preferred areas for global harmonisation are fuelling station standards (rail, road, air, sea), decentralised hydrogen-based heating and power supply.

8.4.2 Pipeline and maritime infrastructure

IEA identifies a strong expansion of the maritime sector to meet the REPowerEU import targets. Offshore hydrogen pipelines, liquid hydrogen and ammonia terminals as well as respective tankers are to be build or strongly increased in numbers[239].

Slightly contradicting decisions to separate the existing natural gas network from the expansion of the hydrogen pipeline network is likely to slow down the building of an EU-wide hydrogen pipeline network[240]. This risk increases the need to offer alternative transportation infrastructures such as road-rail combined transport to reach smaller sized consumers and regions further away from future existing hydrogen networks.

8.4.3 Rail capacity increase

Next to the known improvement requirements for combined transport shipments[241] the need to develop the infrastructure further to match the realistic traffic increase via the Silk Road if Hydrogen is transported via rail (irrespective of the split between hydrogen or ammonia). The added 200%-500% increase for all available corridors based only on the potential volume from the Hyrasia One project and others in the region is desirable to offer a cost-efficient service. In parallel the ferry infrastructures need to be upgraded.

8.5 Combined transport service providers

CTOs
They need to prepare for challenges ahead and market sensing (e.g. Which are active markets and projects?). Following the development of technologies to transport hydrogen (e.g. containers or tank wagons) and the monitoring which relevant regions or projects progress with their hydrogen production ramp-ups that will likely develop transportation needs.

TOs
Analyse needs to expand and adapt to safety standards and potential infrastructure extensions (capacity, weights, speed) and digital transformation.

LSPs
Analyse need to expand and adapt to safety standards for hydrogen transports and containers tracking and utilisation management capabilities.

RUs
Flexibility to accelerate processes between TOs and CTOs to improve punctuality and reliability. Improved secure and high-quality data flows and standardised interoperable digital platform solutions can be a way to improve the service quality of the rail-road system.

[239] IEA (2022) "Global Hydrogen Review"

[240] Banet, Chaterine (2023) "BUILDING EUROPE'S HYDROGEN AND RENEWABLE GAS MARKETS", CERRE Report (https://cerre.eu/wp-content/uploads/2023/02/Building-Europes-Hydrogen-and-Renewable-Gas-Markets.pdf)

[241] Bilgic-Alpaslan (2022) "EU Study on Sustainable Transport Connections between Europe and Central Asia: Presentation of initial findings by the ERBD", European Bank for Reconstruction and Development, Brussels, 30.09.2022 and ICP (2023) "Manifesto on New Silk Road Development", 03.05.2023

IMs

Specific measures towards streamlining processes within EU and at borders on the middle corridor are required. Hydrogen shipments can be pilots to introduce improvements well tested faster and apply successes to other HS codes.

Other regulatory bodies

Include customs and dangerous goods regulatory bodies to allow for fast decisions that are possible if all stakeholders see the benefit (e.g. COVID-19 regulatory fast paths are possible).

8.6 Key take aways for H_2 business ecosystem stakeholders

Green hydrogen as new energy and feedstock source is attractive and there will be sufficient demand to invest into the preparation of capabilities, capacities and business ecosystem building for combined transport.

The hydrogen business ecosystem elaborated before is considerably complex, new and dynamic which poses challenges for all participants to make robust and resilient decisions on which part to play and how to develop in order to grow with the proposed hydrogen roadmap.

Innovate and learn while building a dedicated but cross-regional and cross-sectoral hydrogen business ecosystems to facilitate the acceleration of transporting and using green hydrogen as a new energy source.

Education and social participation to win voters in the EU preventing obstruction because of false facts and to overcome the change inertia that could hinder Europe from profiting from a good starting point. Currently there is still time to craft the future solutions, infrastructures, and services. This situation will likely change is no coherent actions are taken. It must be avoided that slipped time reduces solution space and competitiveness with other regions of the world (see Figure 80).

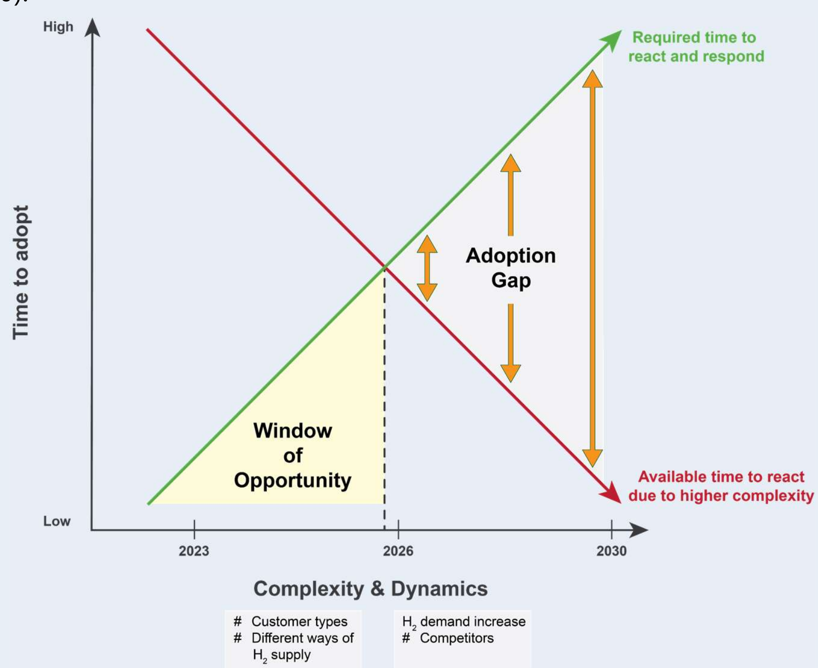

Figure 80: Act now to avoid being caught in the adoption gap (adapted from Bleicher (1999))

9 Making hydrogen business possible for Combined Transport

The evolving business ecosystem for green hydrogen is in a nascent state. The importance of hydrogen and its derivatives for the green transition has been amply demonstrated. There is hardly any doubt that it will be a salient element on the path to decarbonisation and meeting the Fit-for-55, European Hydrogen Strategy and Green Deal programmes' objectives that the EU aims for. Additionally, national and even regional programmes (e.g. Germany's federal state NRW hydrogen roadmap) are supporting the growth of the hydrogen business ecosystem. The study indicates a significant growth potential for intercontinental Combined Transport.

The challenge for **combined road-rail** – especially in the relation to Central Asia and China – is that stakeholders have not yet collectively moved into the relevant development direction yet. If the import goals and the resilience requirements of the power, industry, transport and other sectors are taken seriously, the establishment of road-rail combined transport business ecosystem for hydrogen is "mandatory" as it is the greenest way of land transport in areas where pipelines are not available or cannot be cost-efficiently operated.

Since the option of road-rail combined transport was not included in most academic and industry reports and customers do not actively demand such services today, implementation hurdles and research gaps for shipping hydrogen via rail will have to be closed within the next 5-10 years. In this context, it is critical to:

1) Foster interoperability to increase global efficiency thereby reducing waste of energy/funds
2) Demand stabilisation through regulatory support measures
3) Coordination of actors avoiding the chicken-and-egg problem: reduce set-up time for competitive road-rail infrastructure solutions and not only rely on market efficiency incapable of initiating long-term and large-scale global energy and feedstock supply changes

Combined transport shipments for derivatives such as green ammonia are closer to implementation as it is an already existing business with functioning supply chains. However, capacity and transit time bottlenecks have still been identified on the New Silk Roads Middle Corridor for the forecasted strong demand increase. On the positive side we identified initial opportunities where hydrogen shipment can derive benefits from a consumer perspective. However, there are still commercial and implementation challenges that require resolution through incentivisation and common alignment measures.

The way forward is the proposed **roadmap** or a slightly adapted variant of it depending on the future trajectories of the relevant stakeholders and R&D progresses. Transporting hydrogen via road-rail requires several key processes to establish a cost-efficient and effective system:

1) Provide means enabling **investment security** not only for the producers for green hydrogen but also for the shipping industry
2) Setting of **standards and interoperability** requirements to foster a cost-efficient scaling of capacities and capabilities throughout the supply chain

	Variant 1	Variant 2	Variant 3	Variant 4	Preferred
Pressure	300 bar	500 bar	640 bar	700 bar	640 / 700 bar
Container type	Steel	Carbon-steel	Fibre-steel		
Type of H2	Liquid	Pressurized	Ammonia	Methanol	Depends on location / customer use
Filling station	500 bar	640 bar	700 bar (multi-modal)	700 bar	700 bar (multi-modal)
Container sizes	20ft	30ft	40ft	45ft	45ft
Crane infrastructure	40t	45t	60t	70t	45t / 70t
Train length	650	740	850	-	850

Figure 81: Overview of harmonisation and standardisation requirements of assets to achieve interoperability

Following the dimensional and performance parameters the areas requiring standardisation, harmonisation and interoperability enablement include:

a. Digital standard and platforms to exchange information and documents
b. Document standards for customs and commercial (CIM/SMGS)
c. Additional technical standards (e.g. container connectors, GPS standards etc.)

3) Improvement of the **capacity and efficiency** within Europe and especially on the intercontinental New Silk Road routes (via digitalisation and process improvements highlighted in the Planet LL2 project and the ICP manifesto)

9.1 Recommendations for logistics and industry stakeholders

1) Coordinate the nascent business ecosystem towards a common development path to meet the demand and sizing. If combined road-rail and short sea are to be solutions, decisions need to be made within the next two years to allow for a coordinated build-up of capacities, knowledge and capabilities throughout all stakeholders including: Combined Transport Operators, Terminal Operators, Container Owners and Railway Undertakings and rail Infrastructure Managers on the path to Central Asia and China in close coordination with regulators and associations. Such and approach is important since associations as the building of a green hydrogen business ecosystem is a major task comparable with the electrification of the economy in the late 19th century.
2) Establish intelligent co-opetition-based **business model development** to allow a sufficient capacity and service improvement without a negative impact on cost-levels
3) Continue to foster innovation (R&D) in the area of digitalisation, container design and infrastructure with international and local government support to avoid decision-making inertia. Waiting much longer will be dangerous for seamless functioning of Europe's nascent hydrogen industry and supporting logistics services.
4) Set-up an integrated and coordinated development of a **business-public ecosystem** for combined road-rail transport within the EU and towards Asia. While the rail sector is more energy efficient and greener than most other transport sectors, it is often a late adopter of changes due to its complexity and risk aversity. This high-risk adversity and limited capacity to absorb additional costs requires external intervention by regulators, customers and successful innovations. Therefore, the transformation towards a resilient partner for use and transport of hydrogen from 2030 onwards likely requires closely aligned incentives, stable investment conditions and successful pilots starting in 2025.

5) The feedback collected from the interviews with industry experts is to start running business cases, education and competency building as NH_3 or H_2 which will require new skills and infrastructure. Only if the consumer demand of ammonia and hydrogen are visible in advance the supply chain will be built. A relevant bridging instrument are implementation pilots that can foster learning and standardisation.
6) This study showed that there is a demand for hydrogen and some customer groups (e.g. road or rail transport) will need pure hydrogen and not derivates. The further investing in the opportunities to industrialise the liquid and compressed hydrogen containers is recommended to offer more flexibility and bring hydrogen closer to consumption.
7) The example of the transport of compressed hydrogen from Kazakhstan shows the need for improvement to achieve resilient and multi-modal transport options for hydrogen that is easy to consume on the customer side. The more decentralised supply of smaller consumers is required for locked-out regions, the more relevant the transport prices and usability will become. The upper and right half of the hydrogen transport square are the improvements from business (see Figure 82) the regulatory left is be summarised below.

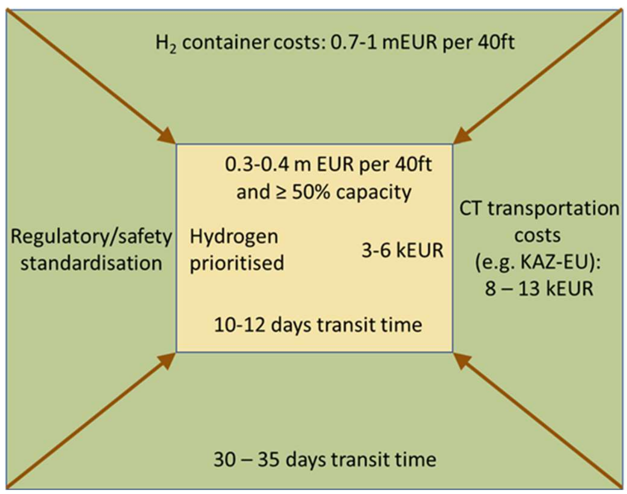

Figure 82: Key targets for compressed hydrogen transport to become viable from Kazakhstan

9.2 Recommendations for regulators

1) Provide regulatory support to build a robust and reality tested infrastructures and service system that customers of combined transport are wanting to use are
   a. Transit time improvement (document, information, wagon, and container standardisation)
   b. Cost level improvements through higher degree of automation
   c. Increase degree of carbon free transport via electrification and a greener energy mix
   d. Robustness of road-rail transport through multiple routes and service providers
   e. Elaborate innovative financing instruments and planning security for the private sector
2) The **New Silk Road** and the economies in the Central East along the New Silk road EU programmes need to be extended beyond EU borders. It has already started (e.g. EU Bank for Reconstruction and Development) but initiatives must encompass the special requirements to foster hydrogen transport options too (liquid, compressed, LOHC or metal hydrides) on all variants of the New Silk Road to achieve competition and resilience.
3) The ongoing legislation for CountEmissions EU should integrate green freight holistically and not solely focussing on CO_2 emissions for the benefit total impact assessment (see ch.

6.4.4). The certification of green hydrogen and ammonia must be globally accepted supported by a more effective measure that matches the complexity of climate change.

4) More detailed research on realistic transport options and their end-to-end pricing are required to avoid high-level and only model-based decisions. Large projects such as the Kazakhstan Hyrasia One are examples showing that narrow-focused decision-making, instead of integrating all supply chain elements and hydrogen sources may lead to wrong figures and transportation mode decisions (such as rail excluded from feasible options and consequently from decisions on R&D programmes for implementation pilots[242]).
5) First evidence in our feasibility study corroborated by others[243] shows that decentralized production or only short distance transport are the key to cost-efficient green hydrogen production that needs to be complemented by efficient import supply chains for countries with high permanent local green energy supply gaps such as Germany.
6) From an end-to-end perspective maritime shipping is expensive for land-bound areas and pipelines will not be available for all geographic regions and for all sources of hydrogen. Therefore, the building of rail as means to transport hydrogen and its derivatives safely and reliably is a no-regret move. The exact type and volume in alignment with a well-funded customer demand analysis per country is a task that has not yet been performed comprehensively.
7) Sources for green energy and production of hydrogen are more than often taken into account. Therefore, a general favourability of one mode of transport seems to be a premature closer that excludes local optima. We recommend a thorough customer segment and location driven analysis that takes into account (1) local access situation (e.g. distance to pipelines), (2) end-to-end transport and conversion needs, (3) availability of suitable transport, and (4) customer demand (hydrogen or its derivatives) from large industry customers to smaller regional SMEs or even household level. Hydrogen, its derivates and hydrogen-based green fuels will likely have different geographic and use-case based justifications.
8) Foster ecosystem building and cross-sector industry dialogue to lower barriers and increase the potential to reap the sector coupling potential of hydrogen[244]. Hoyland et al. (2023) conclude with the *"need for project management, planners, engineers, and so forth, to consider the larger contextual picture (multiple interconnected dimensions on local, regional, and national levels) before proceeding with larger-scale development and implementation of a hydrogen supply chain including production, processing, transportation, and storage*". This is not only true for the hydrogen production but even more so on the transport, trade and consumption side. Hydrogen BE building and piloting must be promoted to achieve mental changes and comprehensive successes that will not only come from isolated funding are critical success factors to avoid stranded assets. Continuation or even extension of the support to shape not only the HBEs but also the awareness of the private consumers. The need of the HBE transformation on the business and private consumer side with initiatives such as Hydrogen Europe, Hydrogen Hubs and

[242] E.g. EU Implementation Support Framework or Hydrogen Europe

[243] Lundblad, Therese et al. (2023)" Centralized and decentralized electrolysis-based hydrogen supply systems for road transportation – A modeling study of current and future costs" Intern. Journal of Hydrogen Energy (48) 12, 88.0223, p. 4830-44

[244] Hoyland, A.S. et al (2023) „Exploring the complexity of hydrogen perception and acceptance among key stakeholders in Norway", Hydrogen Energy (48), p. 7896-7908

Clean Hydrogen is mandatory. It will require considerable behavioural changes and rethinking of past "truths" to make the decarbonisation of EU happen.

This pre-feasibility study has started to analyse the role rail should play in the future hydrogen business ecosystem not only as a consumer but also as a solution provider to ease the supply of green hydrogen or its derivatives and increase Europe's energy supply robustness with minimum GHG emission impact.

9.3 Way forward: Practical next steps to increase momentum

This report showed that the feasibility of hydrogen transport from Central Asia is in reach. Supply and demand will be there with a high likelihood. The next steps to achieve the initial targets are:

1) Support the commencement and continuation of infrastructure and nucleus projects to provide growth incentives for the New Silk Road Middle Corridor (e.g. North Corridor improved significantly until the political interruption caused by the Russia-Ukraine war)
2) Foster **demo train scenarios** to achieve operational maturity, standardisation of parameters and containers, interoperability along the train runs to avoid inefficiencies and incompatibilities of containers, fuelling stations standards etc.
3) Identify areas for hydrogen shipments, ammonia and other forms (Industry & research projects) to foster early learning and specialisation
4) Explore in detail the best one or two transport options to achieve the best interoperability standards for each variant (e.g. storage pressure 500, 640 or 700 bar)
5) Motivate to change consumers' and industry's behaviour alike supported via market and regulatory guidance: e.g. incentivise the change of behaviour towards new heat and power solutions through discounts and foster the production or the depreciation of the investment into the green transition including ramp-up process of the required transport services initially until they achieve a competitive level of interoperable standardised service offerings!

Making effective investment today will be of greater value and less cost than fighting the climate crisis impacts in 15 to 30 years with a far smaller window of opportunity to build competitive knowledge and generate new business potential and jobs for areas where jobs will be lost soon (carbon intensive production, transport, and consumption of fossil fuels).

It is essential to provide an impetus to change the energy, transport, heat and electricity sectors and enable business opportunities supported by incentives that lead to a significant mind and behavioural change.

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11 Appendices

11.1 Central Asia hydrogen production project overview

Azerbaijan

Collaboration	Fortescue Future Industries
Region	
Project	Production of 12 GW of renewable energy and green hydrogen
Performance	12 GW (H_2 unspecified)
Type	Framework agreement
Timeline	Until 2030
Reference	https://www.area.gov.az/en/page/beynelxalq-emekdasliq/beynelxalq-muqavileler/energetika-nazirliyi-ve-fortescue-future-industries-arasinda-berpa-olunan-enerji-ve-yasil-hidrogen-layiheleri-uzre-cercive-muqavilesi
Collaboration	Masdar (Abu Dhabi)
Region	
Project	Wind-to-Hydrogen for production & export purposes
Performance	2 GW (plus future extension)
Type	Implementation agreement
Timeline	Until 2030
Reference	https://news.masdar.ae/en/News/2022/06/05/12/20/Masdar-agrees-to-develop-4-GW-of-clean-energy-projects-in-Azerbaijan

Collaboration	EU
Region	
Project	Transit of green hydrogen to EU
Performance	
Type	MoU
Timeline	
Reference	https://eurasianet.org/azerbaijan-and-eu-agree-to-strategic-energy-partnership

Kazakhstan

Collaboration	Svevind & KazakhInvest
Region	Mangystau
Project	Hyrasia One Wind-to-Hydrogen for production & export purposes
Performance	2 mto H_2 / yr (Input 40 GW project site) or 11 mto ammonia
Type	Project announced, concept design study ongoing
Timeline	Start of production 2030; completion date 2028 (see Reference 2)
Reference	https://energynews.biz/svevind-to-build-20gw-green-hydrogen-plant/
Reference 2	https://www.prosperoevents.com/largest-green-hydrogen-projects-2022/
Project site	https://www.rec-kaz.net/
Reference 3	Interview results

Collaboration	Kazakhstan, France
Region	Studies including 5 regions
Project	Hydrogen Energy Development
Performance	

Type	Planned partnership
Timeline	
Reference	https://astanatimes.com/2022/05/kazakhstan-france-to-forge-partnership-in-hydrogen-energy-development/

Collaboration	Kazakhstan, Germany, Italy, Spain
Region	
Project	Experience exchange and search for solutions in implementation of Green Hydrogen projects
Performance	
Type	Agreement on creation of Green Hydrogen Alliance
Timeline	
Reference	https://dknews.kz/en/articles-in-english/243098-green-hydrogen-alliance-established-in-kazakhstan

Collaboration	Fortescue Future Industries
Region	Atyrau, Mangystau & other regions
Project	Implementation of green hydrogen production projects
Performance	
Type	Framework agreement
Timeline	
Reference	https://hydrogen-central.com/kazakhstan-facilitate-europes-reduced-reliance-fossil-fuels-hydrogen-included/

Turkey

Collaboration	Enerjisa Üretim
Region	Bandırma
Project	Pilot project of green hydrogen production for use in cooling process of Bandırma 2 Natural Gas Cycle Power Plant
Performance	
Type	Project
Timeline	Production started
Reference	https://fuelcellsworks.com/news/turkey-enerjisa-uretim-started-green-hydrogen-production-at-bandirma-energy-base/

Collaboration	Aspilsan Energy, Enerjisa Üretim, Eti Maden, TÜBTAK MAM, South Marmara Development Agency
Region	Balıkesir
Project	1st green hydrogen production plant in TR
Performance	
Type	Collaboration protocol, project
Timeline	
Reference	https://hydrogen-central.com/turkey-establish-green-hydrogen-power-plant-balikesir/

Armenia

Collaboration	Ministry of Infrastructure, HyGreenCo (Sub of French Solges-Energy). Children of Armenia Fund (COAF)
Region	Debet

Project	Industrial demonstrator for production of green hydrogen from solar power to feed into Smart Grid
Performance	
Type	Partnership agreement for construction of demonstrator project
Timeline	
Reference	https://fuelcellsworks.com/news/armenia-moving-closer-to-green-hydrogen-production/

Turkmenistan

Collaboration	OSCE, Turkmenian Ministries, Turkmengas, Turkmenoil. Turkmengeology, Turkmenchemicals
Region	
Project	Pilot for a green hydrogen roadmap for Turkmenistan with international collaboration (Russia, Japan, South Korea, UK)
Performance	
Type	Roundtable discussions
Timeline	
Reference	https://www.osce.org/centre-in-ashgabat/518064

Uzbekistan

Collaboration	(ACWA) Saudi Arabia
Region	Chirchiq
Project	Production of green hydrogen for existing ammonia production facility
Performance	3 kto H_2 p.a.
Type	Project
Timeline	Commissioning end of 2023
Reference	https://www.hydrogeninsight.com/production/on-a-fast-track-uzbekistan-announces-first-green-hydrogen-and-ammonia-projects/2-1-1390987

Collaboration	(ACWA) Saudi Arabia
Region	
Project	Production of green ammonia
Performance	500 kto ammonia p.a.
Type	Feasibility study
Timeline	End of 2024
Reference	https://www.hydrogeninsight.com/production/on-a-fast-track-uzbekistan-announces-first-green-hydrogen-and-ammonia-projects/2-1-1390987

Collaboration	(ACWA) Saudi Arabia
Region	
Project	Green hydrogen project development & investment roadmap; wind-to-hydrogen
Performance	
Type	Investment & collaboration agreement
Timeline	
Reference	https://fuelcellsworks.com/news/saudi-arabia-wants-to-produce-green-hydrogen-in-uzbekistan/

11.2 Interviewees

Organisation	Interviewee	Core topics
DB Cargo BTT	Bjarne Regenbrecht (Head of Chemicals & Hydrogen Transport Solutions) Luisa Koester (Project Manager Chemicals & Hydrogen Transport Solutions)	H2 shipping via rail
Hyrasia One, Kazakhstan (Project developer Svevind)	Dr. Rene Pforte (Chief Business Development Officer, Svevind Energy GmbH)	Hydrogen production
Clean Hydrogen JU	Bart Biebuyck (Executive Director)	Hydrogen development
Unleash Future Boats	Stephanie Engelhard (COO)	
BASF AG	Samer Gandour	Transport options
	Dr. Thorsten Bieker	Transport options, pilot potentials
Bertschi AG	Ueli Bruder, Head Technical Department	H2 propulsion for trucks
Deutsches Zentrum für Luft- und Raumfahrt	Victoria Carolin Jäger et al.	H2 shipment via rail
Alpega	Elina McCafferty	H2 Calculation
Duisport	Mr. Cao, Mr. Schwarz	
Chesterfield Special Cylinders PLC	Mrs. Sonia Naoui (Director of Hydrogen Business Development)	
Diverse manufacturers of containers	Several manufacturers or leasing companies that want stay anonymous	

11.3 Methodology

The key research method the paper leans onto is participatory action research[245] due to involvement in several areas of the hydrogen business ecosystem and through expert interviews.

Bottom-up and top-down assessment of forecasts were performed to reality test the estimations and their often not explicitly stated assumptions. Linearisation to achieve 2050 targets in line with the EU approach was applied in rare occasions where there was no external data available within reasonable effort and expenses.

Sustainability transitions are non-linear and complex due to their multiple complex interactions not only through the supply chain but technical, political, economic, regulatory and socio-economic dimensions[246].

Qualitative interviews are used to substantiate practical progress to corroborate assumptions and collect practical experience on the status quo derived from own practical experience and literature research. Super forecasting-based projections were applied where necessary[247]. For the technology and business road mapping past projects and literature (see Abele 2006) were applied.

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