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Study Findings Report

Green Hydrogen Transport Scenarios: From Kazakhstan to Europe

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Imprint

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Content

Executive Summary

Executive Summary

Study Goals

This executive summary is for a transport study for export of green hydrogen from Kazakhstan to Europe. The study is understood to be at concept level in order to explore and evaluate potentials and a range of options for transport rather than going into engineering detail for only one specific option. The study was made from a purely techno-economic point of view. The assessment of geo-political implications of potential transport options via the Middle Corridor was not in the scope, but should be undertaken nevertheless, e.g. in a separate follow-up study.

The goals of the concept study carried out by Fichtner are defined in the following:

1. Analyze existing logistic chains (i.e. pipeline transmission of natural gas and oil, as well as rail network) the country of Kazakhstan.
2. Do research for transport costs of green hydrogen (H_2) and ammonia (NH_3) which can be expected via different transport options.
3. Apply those findings to the use-case of H_2/ NH_3 delivery from Kazakhstan to Europe and give recommendation of a feasible transport option via the Middle-Corridor.

The underlying approach to meet the study's goals is a high-level assessment of feasible transport options between Kazakhstan and South-East Europe, transporting either H_2 or NH_3 to the border line of South-East Europe. Fichtner outlines the following activities:

- Summarizing findings of relevant literature on the topic of H_2 transportation options and costs.
- Suggesting a feasible transport scenario between Kazakhstan and Europe, taking into account technical and economic aspects.

The analysis of existing logistic chains in Kazakhstan, as well as the findings of the literature review on H_2 transport options are part of the report and not included in the executive summary, which discloses the findings of the H_2 transport assessment between Kazakhstan and South-East Europe.

Hydrogen Transport Assessment

For each route section along the so-called Middle Corridor[1] between Kazakhstan and South-East-Europe, several transport options from a techno-economic point of view have been discussed in the light of pre-defined use-cases and indicative cost estimates for the transport-related costs of gaseous H_2 have been assessed. The assessment of future costs - in this case levelized costs of transport (LCOT) as well as LCOH - is subject to uncertainties in the respective target years 2030 and 2040 which is why the provided cost figures must be regarded with caution. Nevertheless the assessment considered the feasibility of various transport options for future H_2 and NH_3 export from Kazakhstan to South-East-Europe, based on technological, infrastructural and economic challenges that will be encountered if the defined use-cases are drawn to the discussion.

[1] The Middle Corridor is defined in this study as a transport route between Kazakhstan and South-East-Europe crossing the Caspian Sea, Azerbaijan, Georgia and Turkey (ending at the Greek or Bulgarian border) or across the Black Sea (ending either at Constanta or Burgas).

With regards to trans-border pipeline transport uncertainties remain which cannot be further assessed in this study. This primarily concerns the availability and capacities of future pipeline transmission networks outside Kazakhstan and Europe. One pre-requisite for pipeline-based H_2 export in Kazakhstan along the defined transport route is an off-shore pipeline section across the Caspian Sea, which - to the date of writing and to the best knowledge of the authors - has so far not been publicly discussed yet. Furthermore, H_2 pipeline agendas in the countries of Azerbaijan, Georgia and Türkiye are not yet fully defined or accessible in order to make a solid evaluation how feasible the scenario of a pipeline connection among those countries can be in the end.

To decrease dependancies on future partner countries and respective stakeholders H_2 transport can potentially by-pass Türkiye if H_2 pipeline transmission ends at a Black Sea port in Georgia. For this option, H_2 would have to be converted first to NH_3 or LH_2 nearby the respective export port. As an alternative, NH_3 can be delivered via tankers across the Caspian Sea and via pipeline across Azerbaijan and Georgia to a Georgian Black Sea port. From there NH_3- or LH_2-tankers can be loaded for the last route-section and finally deliver a green product to Europe via international waterways. What makes this option advantageous, is the increased flexibility regarding the port of destination for NH_3 or LH_2 unloading as respective tankers would not be restricted to European Black Sea ports such as Burgas or Constanta due to the access to the Mediterranean Sea and the Atlantic ocean via marine straits Bosporus and Gibraltar. On the other hand, process steps in the supply chain for NH_3 or LH_2 conversion (as well as H_2 re-conversion) and associated efficiency losses can lead to higher transport costs when partly shipping the product to Europe compared to pipeline transmission via Türkiye. The effect on cost increase due to NH_3 conversion can be slightly mitigated if NH_3 production takes place in Kazakhstan which is assumed to provide for low electricity prices - and hence low production costs - in the future compared to other countries along the Middle Corridor. Also, cost reductions for the final product can be additonally achieved, when NH_3 is not subject to re-conversion at the European import ports. If and to what extend green NH_3 as a final product can be an attractive alternative to green H_2 depends among other things on the willingness-to-pay for H_2 and actual demand for NH_3 in the target markets.

Figure 1 and Figure 2 show the potential transport route between Kazakhstan and South-East-Europe and provide an overview of the transport-related costs for H_2 at the end of each route section.

Main findings are:

- For the Small scale use case in 2030 both H_2 export exclusively via pipelines, as well as NH_3 export via a combination of NH_3 tankers and intermediate NH_3 pipeline transmission are competitive from a cost perspective with a slight advantage for H_2 export via pipelines
- For the Large scale use case in 2040 the assessment suggests H_2 transport via pipelines, rather than transport by ship.
- As an alternative to pipeline transport via Türkiye the pipeline tranmission could end at Georgian Black Sea ports. From there shipping of NH_3 in the Small scale use case in 2030 shows lower transport-associated costs (i.e. conversion, shipping, re-conversion) compared to LH_2. The option of LH_2 can outcompete NH_3 by 2040 if, for example, electricity costs for conversion and re-conversion decrease over time and provided that respective ship types are available by then
- NH_3 transport via rail is considered not feasible due to the immense need for infrastructure development of rail networks and fleet expansion in the light of the large volumes of NH_3

assumed in the assessment as well as lacking permission for the transport of hazardous goods below the Bosporus through Türkye via the Maramary tunnel.

- It is critical to point out, that the transport assessment of the study at hand did not take into account intermediate project developments during the scale-up phase, in which transport volumes are of much lower magnitude in the beginning and increase over time. Such scale-up use cases were not defined for this study and accordingly the findings of this study might not be applicable for a scale-up scenario. Thus, the option of rail transport during the scale-up phase, e.g. via alternative routes must not be discarded and are advised to be investigated in additional studies.

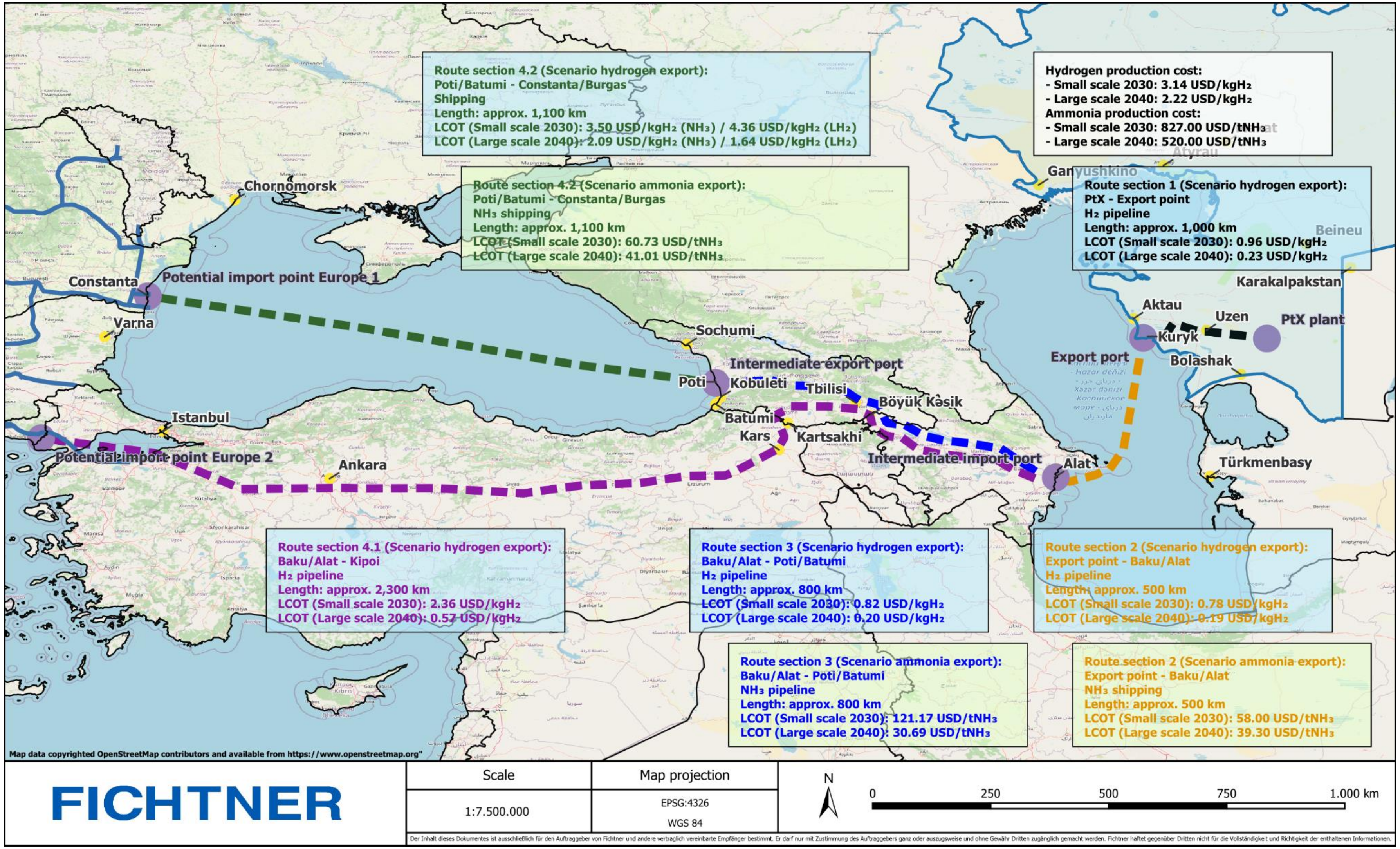

Figure 1: Overview of route sections between Kazakhstan and South-East-Europe

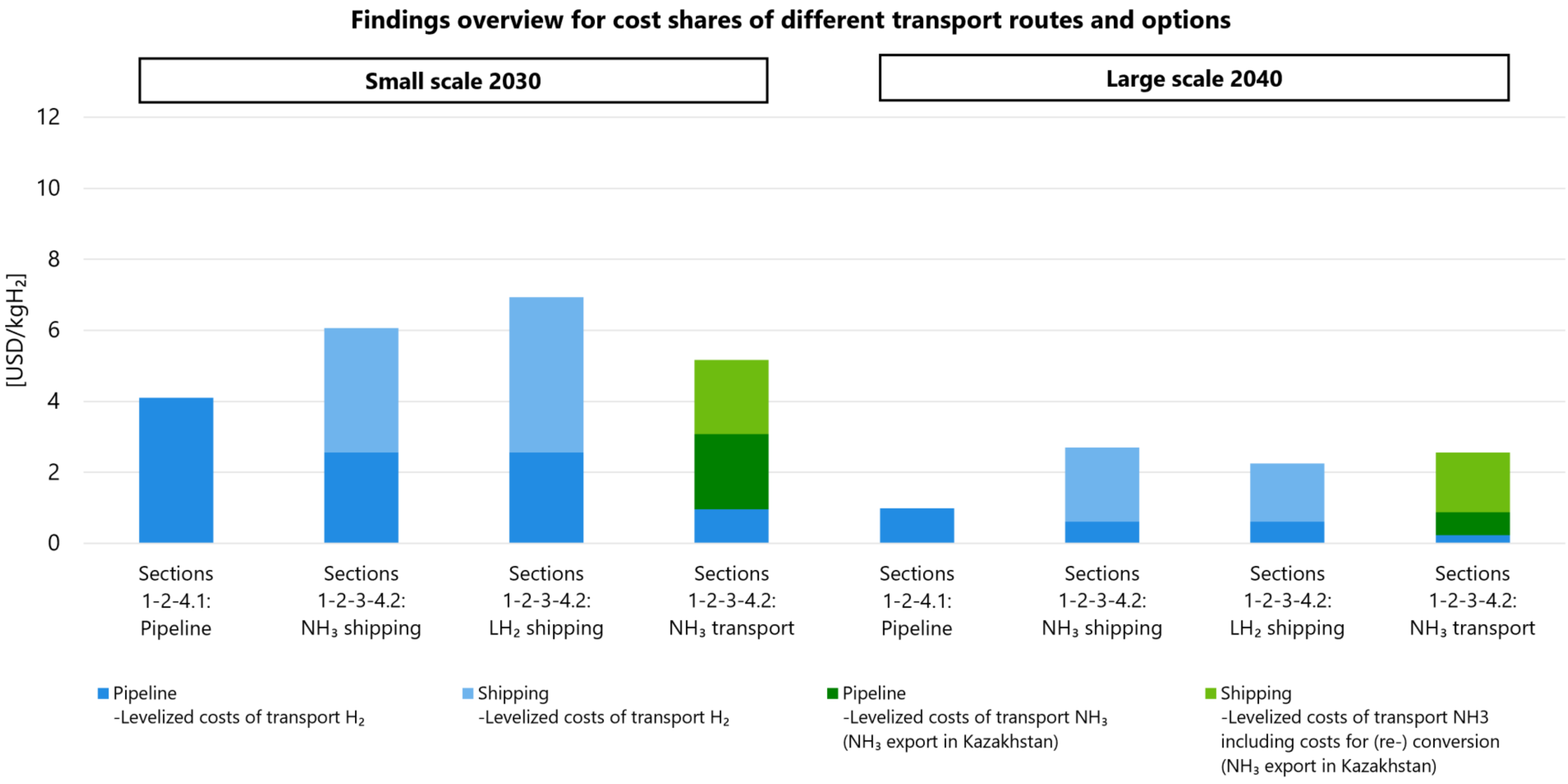

Figure 2: Findings overview for cost shares of different transport routes and options.

01

Introduction

1 Introduction

1.1 Context

Through the agenda of the "Global Hydrogen Diplomacy" the client supports the German Federal Foreign Office in establishing hydrogen-related partnerships between Germany and countries whose national economies currently strongly depend on the export of fossil fuels. In the light of decreasing demand for fossil energy and the global need for carbon-neutral energy in the future, Kazakhstan will have to deal with the transition of the energy sector as well as fundamental shifts in economic value creation within its economy.

With large potentials for wind power and wide availability of land in Kazakhstan (indicated in blue in Figure 3) the domestic production and export of green hydrogen (H_2) and ammonia (NH_3) - i.e. exclusively produced using renewable energies (RE) such as wind and solar power - embodies an opportunity to both decrease the dependence on fossil fuels and participate in a global H_2 economy, creating long-term benefits for the Kazakh state and partners.

In case, H_2 can be produced economically on large scales in Kazakhstan, feasible transport routes and options must be evaluated for the delivery of green H_2 and NH_3 to Europe. This is needed because the European Commission's goal is to import 10 million tons of renewable H_2 by 2030 in addition to its own H_2 production [94]. This is planned to cover the projected future demand of 20 million tons of H_2 in 2030 and to lay the foundation for supply for an increasing demand after 2030 [95]. A partnership between the European Commission and the Kazakh government was signed at the World Climate Conference in 2022 for exactly these purposes. [96]

The route subject for investigation through this study is the so-called Middle Corridor, which is indicated in Figure 3.

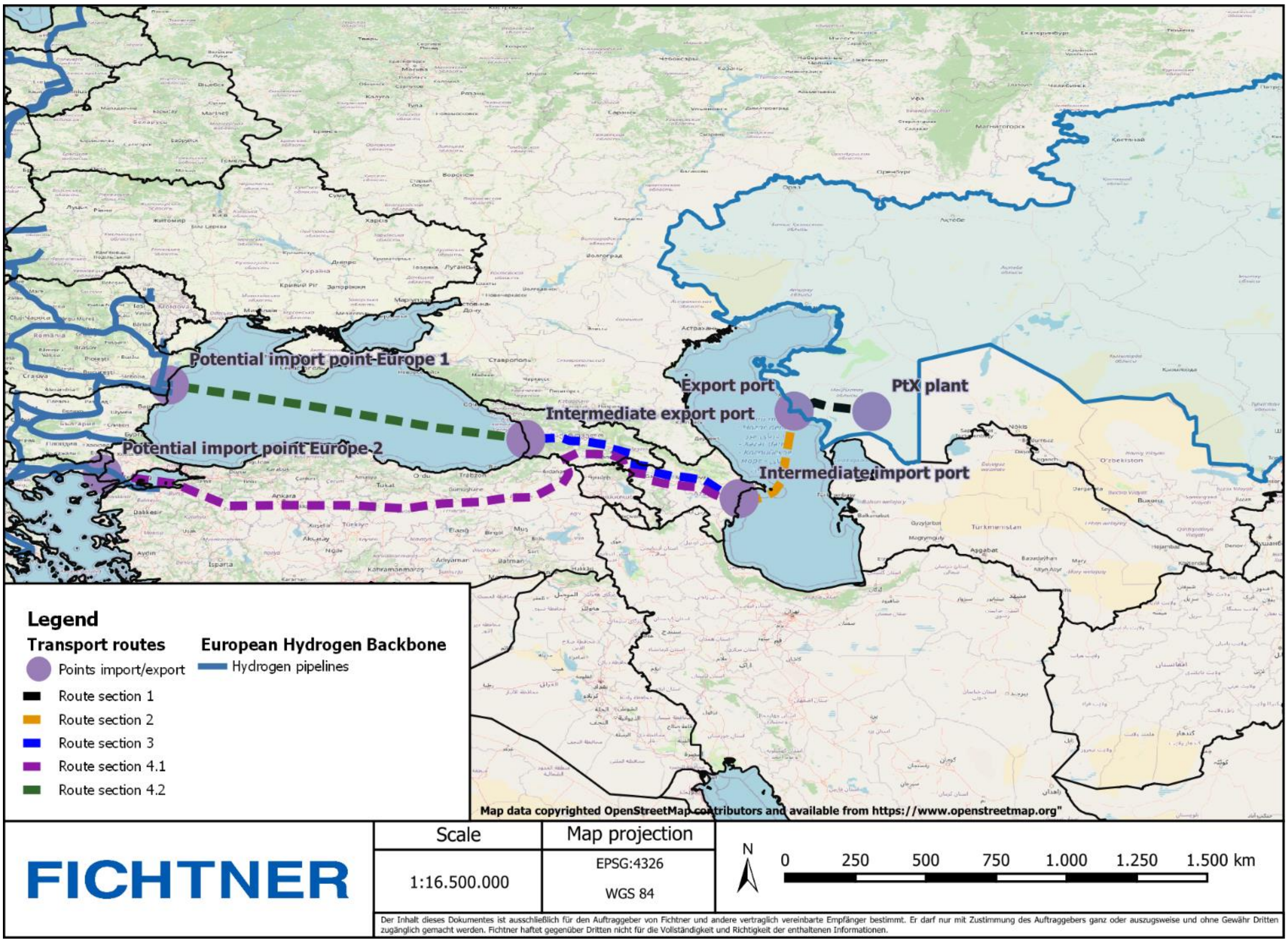

Figure 3: So-called Middle Corridor transport route between Kazakhstan and South-East-Europe

1.2 Scope and goals of the study

The study is understood to be at concept/ pre-feasibility level in order to explore and evaluate potentials and a range of options for transport (also referred to as transmission, see hydrogen value chain in Figure 4) rather than going into engineering detail for only one specific option. It should be noted that the study by Fichtner will be made from a purely techno-economic point of view. The assessment of geo-political implications of potential transport options via the Middle Corridor is not in the scope, but should be undertaken nevertheless, e.g. in a separate follow-up study.

Looking at the H_2 value chain (Figure 4), the study's focus is on H_2 Transmission (midstream), i.e., after Production (upstream) and before Distribution and Demand (downstream).

Figure 4: Hydrogen value chain

The underlying approach to meet the study's goals is a high-level assessment of feasible transport options between Kazakhstan and South-East Europe, transporting either H_2 or NH_3 to the border line of South-East Europe. Fichtner outlines the following activities:

- Summarizing findings of relevant literature on the topic of H_2 and NH_3 transport options and costs.
- Suggesting a feasible transport scenario between Kazakhstan and Europe, taking into account technical and economic aspects.

General assumptions and restrictions about the study have been defined in the initial proposal by Fichtner, as well as the Exposé which was approved by the client and submitted at the beginning of the study.

Figure 3 shows the area of research, indicating the general understanding of a potential transport route via the so-called Middle Corridor. Fichtner divides this transport route into several route sections, defined by geographic boundaries, such as coast lines and the border line of East Europe (i.e. Black Sea coastline of Bulgaria and Romania, as well as borderline between Türkiye and Greece or Bulgaria).

Study goals

The goals of the study carried out by Fichtner are defined in the following:

1. Analyze existing logistic chains in Kazakhstan (i.e. pipeline transmission of natural gas and oil, as well as rail network).
2. Do research for transport costs of green H_2 and NH_3 which can be expected via different transport options.
3. Apply those findings to the use-case of H_2/ NH_3 delivery from Kazakhstan to Europe and give recommendation of a feasible transport option via the Middle Corridor.

To meet the study's goals, the strategy for project execution has been described in an exposé, along with the assumptions, limitations and methods applied by Fichtner. This reproduces the proposed project work as it has been defined in the initial proposal.

1.3 Content of the Report

In respect to the defined study goals, Fichtner proposes three work tasks. The working results of the three work tasks are reproduced in the respective report chapters 2, 3 and 4.

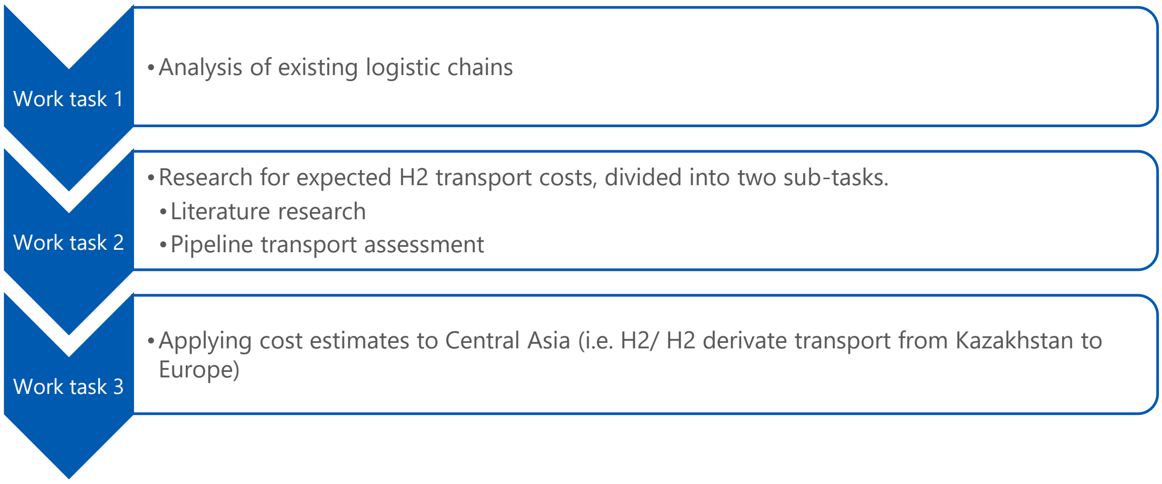

Figure 5: Work tasks of the study by Fichtner

It should be noted that Fichtner will undertake its' analysis on the basis of existing logistic chains. In the conclusion of the study Fichtner will give remarks on anticipated weak/ critical sections (bottlenecks) in the proposed logistic chain(s) between Kazakhstan and South-East Europe.

In chapter 2 existing logistics chains in the country are analyzed, namely

- oil transmission pipelines,
- natural gas transmission pipelines,
- Kazakh rail network.

Technical basics for pipeline transmission are given in the appendices 7.1 and 7.2 to provide a better understanding of the technical configuration of pipeline-associated transport systems, as well as aspects of repurposing existing natural gas pipelines for H_2 transport.

Chapter 3 is dedicated for the findings of a literature review on H_2 transport. Subject for review are selected studies that have been provided by the client. The key findings of those studies are summarized and discussed for the following assessment on feasible transport options for H_2 and NH_3 export to South-East Europe.

A generic assessment of domestic pipeline transport of H_2 from the H_2 production site to an export point at the Kazakh coast of the Caspian Sea, as well as an analysis of feasible export routes and transport options to South-East Europe via the Middle-Corridor is given in chapter 4. As this chapter discusses the various transport options, cross-references are given to the appendix in which further techno-economic aspects are provided in more detail.

02

Analysis of existing Logistic Chains in Kazakhstan

2 Analysis of existing Logistic Chains in Kazakhstan

Kazakhstan is a large energy producer of oil and natural gas and a net exporter of fossil fuels. The oil and gas-related sectors accounted for about 17% of Gross Domestic Product (GDP) in 2020 [1]. Accordingly, associated pipeline transmission networks for natural gas and oil are operated across the country and its neighboring states. Additionally, several goods other than oil and gas are transported via an extensive railway network.

2.1 Natural Gas Transmission

2.1.1 General Remarks

The main gas company of Kazakhstan is “QazaqGaz JSC”. It is a state-owned company by the sole shareholder “Samruk-Kazyna JSC” which is the Kazakh national welfare fund. The company’s activities extend along the natural gas value chain from exploring and operating gas fields, constructing and operating of gas pipelines and storage facilities to the management and sales of gas through transportation networks to international and domestic customers as well as providing international gas transit. The QazaqGaz group includes 12 subsidiary companies for different activities in the gas sector. Companies relevant for the operation and maintenance of the Kazakh main pipeline grid are the pipeline operators “Intergas Central Asia JSC”, “Asian Gas Pipeline LLP” and “Beineu-Shymkent Gas Pipeline LLP”. [32]

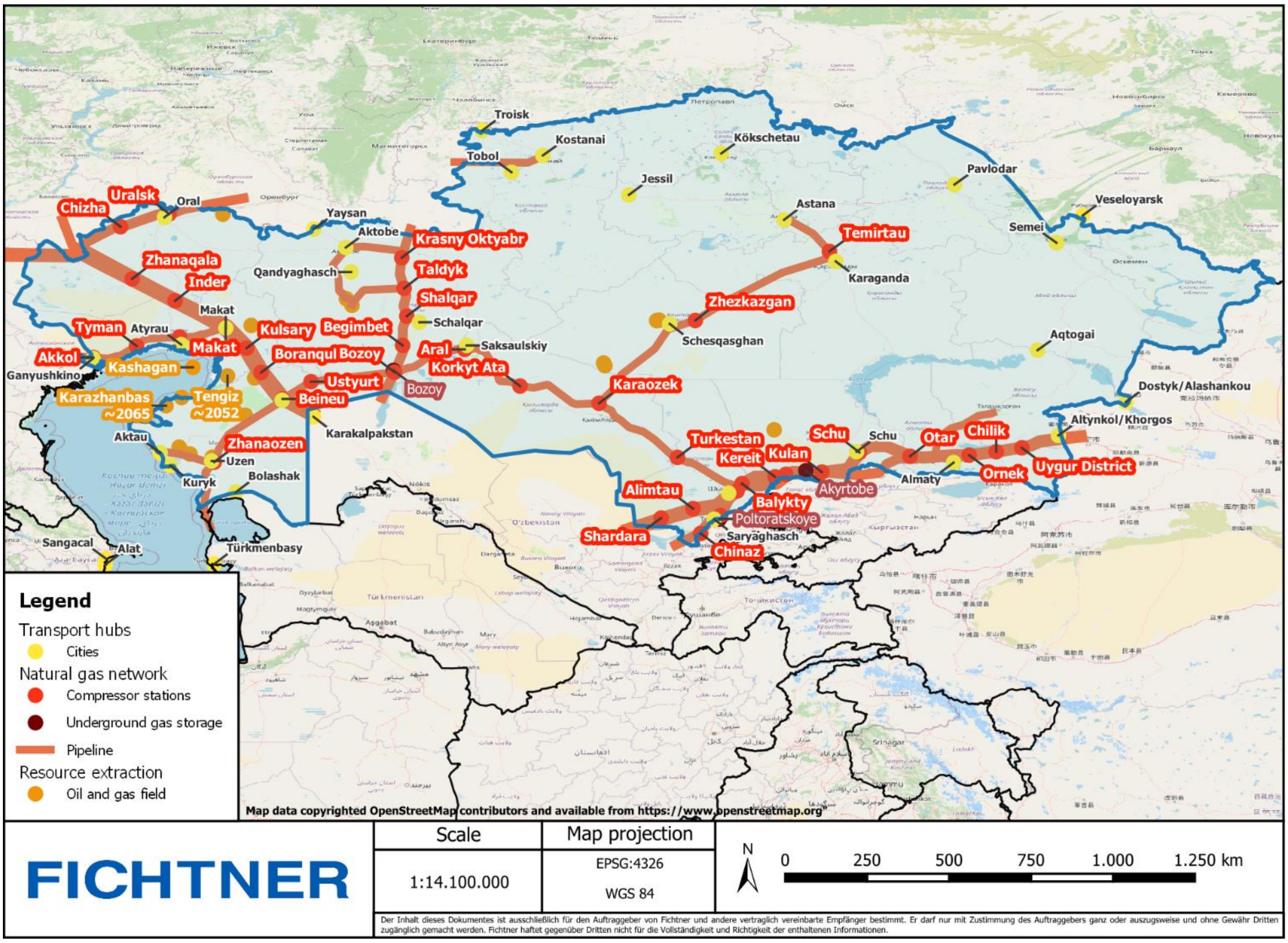

Figure 6: Kazakh main natural gas network

2.1.2 Production

The natural gas production totals around 55.1 bcm in 2020. The amount of gas produced has increased yearly by 4% since 2010 due to rising production and development of new oil and gas deposits. Till 2030 a further increase to approximately 87.1 bcm is expected. More than a half of the produced natural gas is associated with the crude oil production. 31% of the extracted gas was re-injected in the oil deposit to maintain the pressure needed for high oil production rates and 14% was used by companies near the production site for energy generation [15]. Only 55% were sent for processing. [1]

The gas production takes place in various oil and gas fields on-shore and off-shore on the Caspian Sea. The so-called “big three” are Kazakhstan’s largest oil and gas fields for which additional expansions are expected in the future. 80% of gross domestic production and 70% of commercial gas supply belong to these production sites in 2020. These production sites are

- Karachaganak (on-shore gas condensate field) 36.7%,
- Tengiz (on-shore) 26.7%,
- Kashagan (off-shore) 16.7%.

These three oil and gas fields are all located in the western part of Kazakhstan. There are different oil and gas companies from foreign countries that own the right to use each of these fields. The Kazakh state and KMG JSC hold shares in the use of these fields in the amount of only 8-20%. [1, 15]

2.1.3 Transmission Network

According to the Kazakh bureau of national statistics the main gas pipeline network consists of 16,394 km transmission pipelines (2021) [6].

QazaqGaz owns the largest transmission pipeline network in Kazakhstan. Together with shares in international pipeline sections connecting Kazakhstan and neighboring countries the total length of pipelines owned amounts over 20,600 km in 2021. Furthermore, via the subsidiary company "JSC KazTransGas Aimak" QazaqGaz owns and operates the Kazakh gas distribution network with over 59,000 km of pipelines as well. For the operation and maintenance of the main gas pipelines subsidiary companies of QazaqGaz are in charge. [33]

Intergas Central Asia is a fully owned subsidiary and the main pipeline operator in Kazakhstan. This company is responsible for about 12,532 km of gas pipelines. In 2021 54.8 bcm natural gas was transported through this network. 64% of the transported gas was transit gas from neighboring countries, 14% was Kazakh gas meant for export and 22% was transmitted for the utilization in the Kazakh domestic market. [33]

Asia Gas Pipeline is a partly owned (50% QazaqGaz, 50% PetroChina) subsidiary pipeline operator. 41.6 bcm natural gas was transmitted through pipelines in their operation. Most of the gas that was transported was transit gas with a share of 85%, 12% was Kazakh export gas to China and only 3% was transported for the domestic market. [33]

The company Beineu-Shymkent Gas Pipeline is a further partly owned (50% QazaqGaz, 50% PetroChina) subsidiary. In 2021 a transportation volume of 10.7 bcm was handled. The export gas reached a share of 46% and gas for the domestic market accounted for 54%. [33]

Table 1 shows the routes of the main natural gas pipeline sections of Kazakhstan in order of the pipeline operators.

Table 1: Main natural gas transmission pipeline sections in Kazakhstan

Pipeline operator/ pipeline section	Length [km]	Capacity [bcm/a]	Diameter [mm]	Pressure [bar]	Number of strands
Intergas Central Asia JSC					
Central Asia Center Gas Pipeline (CAC)	855 [34]	80 (all together) [35]	1,000/1,200/1,200/ 1,400/1,200 [36, 37]	54/54/74/74/ 54-74 [34]	5 [34]

Pipeline operator/ pipeline section	Length [km]	Capacity [bcm/a]	Diameter [mm]	Pressure [bar]	Number of strands
Makat-North Caucasus Pipeline	370 [38]	42 [38]	1,400 [38]	74 [38]	1 [38]
Okarem-Beineu Pipeline	472 [38]	7.2 [39]	1,000-1,200 [38]	54 [38]	1 [38]
Bukhara-Ural pipeline	570/570 [38]	15 [40]	1,000/1,000 [38]	55 [38]	2 [38]
Saryarka pipeline	1061 [41]	2.2 [41]	800 [41]	98 [38]	1 [38]
Bukhara-Tashkent-Bishkek-Almaty Gas Pipeline (BGR-TBA)	760/760 [38]	12 (all together) [42]	700, 800, 1,000/700, 800, 1,000 [38]	54 [38]	2 [38]
Zhanaozen-Zhetybay-Aktau Pipeline	149 [38]	3.4 [43]	700 [38]	40 [38]	1 [38]
Soyuz Pipeline	382 [38]	26 [44]	1400 [38]	74 [38]	1 [38]
Orenburg-Novopskov Pipeline	382 [38]	18 [45]	1200 [38]	54 [38]	1 [38]
Kartaly-Rudny-Kostanai Pipeline	227 [46]	5.36 [46]	800/700 [38]	-	1 [38]
Gazli-Shymkent Pipeline	309 [38]	4.3 [47]	1200 [38]	74 [38]	1 [38]
Almaty-Taldykorgan Pipeline	264 [38]	-	5 [38]	94 [38]	1 [38]
Zhanazol-CS-13 Pipeline	157 [38]	5.2 [48]	800 [38]	64 [38]	1 [38]
Zhanazol - Aktobe Pipeline	241 [38]	0.697 [48]	500 [38]	44 [38]	1 [38]
Aktobe-CS-14 Pipeline	136 [38]	-	500 [38]	55 [38]	1 [38]
Asia Gas Pipeline LLP					
Central Asia Gas Pipeline	1,303/1,303/1,303 [38]	55 (all together) [32]	1,000/1,000/ 1,000 [32]	98 [32]	3 [38]

Pipeline operator/ pipeline section	Length [km]	Capacity [bcm/a]	Diameter [mm]	Pressure [bar]	Number of strands
Beineu-Shymkent Gas Pipeline LLP					
Beineu-Bozoy-Shymkent Pipeline	306/1,143 [49]	13 [49]	1,000/1,000 [49]	74/98 [49]	1 [49]

2.1.4 Underground Gas Storage

The Kazakh natural gas infrastructure holds three underground gas storage facilities with a total active capacity of 6.5 bcm. The biggest underground gas storage facility is located in Bozoy - a depleted gas field which was repurposed for natural gas storage with a capacity of 5.9 bcm (expanded capacity to 5.9 bcm in 2021). Other storage facilities with minor capacity are Poltoratskoye (0.35 bcm) and Akyrtobe (0.3 bcm) that both use aquifer for gas storage [52]. [1]

Depleted oil and gas reservoirs or aquifers are pore storage facilities that are gastight rock layers. Oil and gas reservoirs are well suited for the purpose of gas storage in general, as information on the rock, the operating behavior and the operating pressures as well as the required equipment are already available. The disadvantage is the lack of knowledge of gas tightness and permeability in the event of storing H_2 and requires extensive research. The usability for H_2 storage has not yet been fully explored. When H_2 is stored in depleted oil and gas fields or aquifers there is the possibility for contact with bacteria which leads to the production of toxic and corrosive H_2 sulfide or reactions with hydrocarbons that impurify the H_2. H_2 is then lost as a result. Furthermore, sediments can occur which clog the porous rock. Salt caverns provide a reliable underground storing option which are already in operation for storage of H_2, e.g. in Great Britain. [53, 54]

2.1.5 Export

The Kazakh gas system was mostly constructed as a part of the former Soviet Union gas system. It is characterized through large transit volumes and swaps. Therefore, numbers for import and export gas volumes reported by pipeline operators, customs authorities, the statistical agency and other institutions are conflicting. According to pipeline operator QazaqGaz 19.7 bcm natural gas were transported through pipelines for export in 2020 [32]. The Kazenergy Association published a value of 16.7 bcm for 2020 and Kazakh customs data mentioned 18.8 bcm of export gas. Exports to China amounted 7.4 bcm in 2020. Most of the remaining export gas (9 bcm) went to Russia. Only 0.1 bcm gas was exported to Uzbekistan and 0.3 bcm to Kyrgyzstan. [1, 51] Important pipeline sections for the natural gas export and transit are described below.

- There are mainly 3 export and transit pipelines to Russia. The Central Asia Center gas pipeline with an annual capacity of 80 bcm links Turkmenistan and Uzbekistan to the Russian gas system via a pipeline section through western Kazakhstan to the border crossing in the northwest. Starting at Makat in Kazakhstan the Makat-North Caucasus pipeline with a potential yearly throughput of 42 bcm runs along the northern coast of the Caspian Sea to Russia. Via Bukhara-Ural pipeline annually 15 bcm gas can be transported. The pipeline starts in Uzbekistan and heads north through Kazakhstan to Russia. [1]
- For the gas export and transit to China the Central Asia pipeline is operational. The pipeline runs from Turkmenistan through Uzbekistan and across southeast Kazakhstan to China. The capacity of the pipeline totals 55 bcm per year and is mostly used for Turkmen gas and minor volumes of Uzbek and Kazakh gas. [1]
- The Bukhara-Tashkent-Bishkek-Almaty pipeline transports Uzbek gas through south Kazakhstan to Kyrgyzstan and supplies Almaty in Kazakhstan. The maximum capacity of the pipeline is 12 bcma. [1]
- The Beyneu-Bozoy-Shymkent pipeline functions as a link between gas production in western Kazakhstan and the central and eastern regions. The pipeline is designed for a quantity of 13 bcm natural gas per year. [1]

2.1.6 Import

In the east and north of Kazakhstan as well as in parts of the south the connection to the gas supply with Kazakh gas is not completely ensured requiring imports from neighboring countries. Nevertheless, imports have been reduced in recent years through the expansion of the domestic gas infrastructure. According to Kazakh custom statistics [51] 9.7 bcm natural gas was imported in 2020. The Kazenergy Association quantifies the imports with 4.3 bcm in the same year. Origins of the gas were Russia with 3.4 bcm, Uzbekistan with 0.8 bcm and Turkmenistan with 0.1 bcm.

Transit gas transported through Kazakhstan between neighboring countries totals 62.7 bcm in 2020. The biggest share of transit volume belongs to the Russia-Russia transit (25.7 bcm) and the transit from Turkmenistan (28.6 bcm). [51]

2.2 Crude Oil Transmission

2.2.1 General Remarks

“JSC National Company KazMunayGas” (KMG JSC) is a Kazakh oil and gas company. The business area covers exploration, production, refining, transportation and services in the hydrocarbons sector. Main shareholders of the company are the national welfare fund “Samruk-Kazyna JSC” (owned by the government of Kazakhstan) (87,42%) and the National Bank of Kazakhstan (9,58%). As a holding KMG JSC owns shares of 56 companies which are located in Kazakhstan [14]. Relevant companies related to that holding in the midstream sector are “KazTransOil JSC” (KTO JSC), the “Caspian Pipeline Consortium” (CPC) and “Karachaganak Petroleum Operating B.V.” (KPO) for pipeline transport as well as “NMSC Kazmortransflot LLP” (KMTF) for maritime transportation. [15] “

KazTransOil JSC" itself owns shares of further companies in the transport segment. "MunaiTas LLP - North-Western Pipeline Company" and "Kazakhstan-China Pipeline LLP" are thereby significant in terms of oil pipeline transport in Kazakhstan. [16]

In 2020 the oil and gas related sectors accounted for 17% of Gross Domestic Product (GDP) according to the annual energy sector review of Kazakhstan by the International Energy Agency (IEA) [1]. The following is mainly based on the same report.

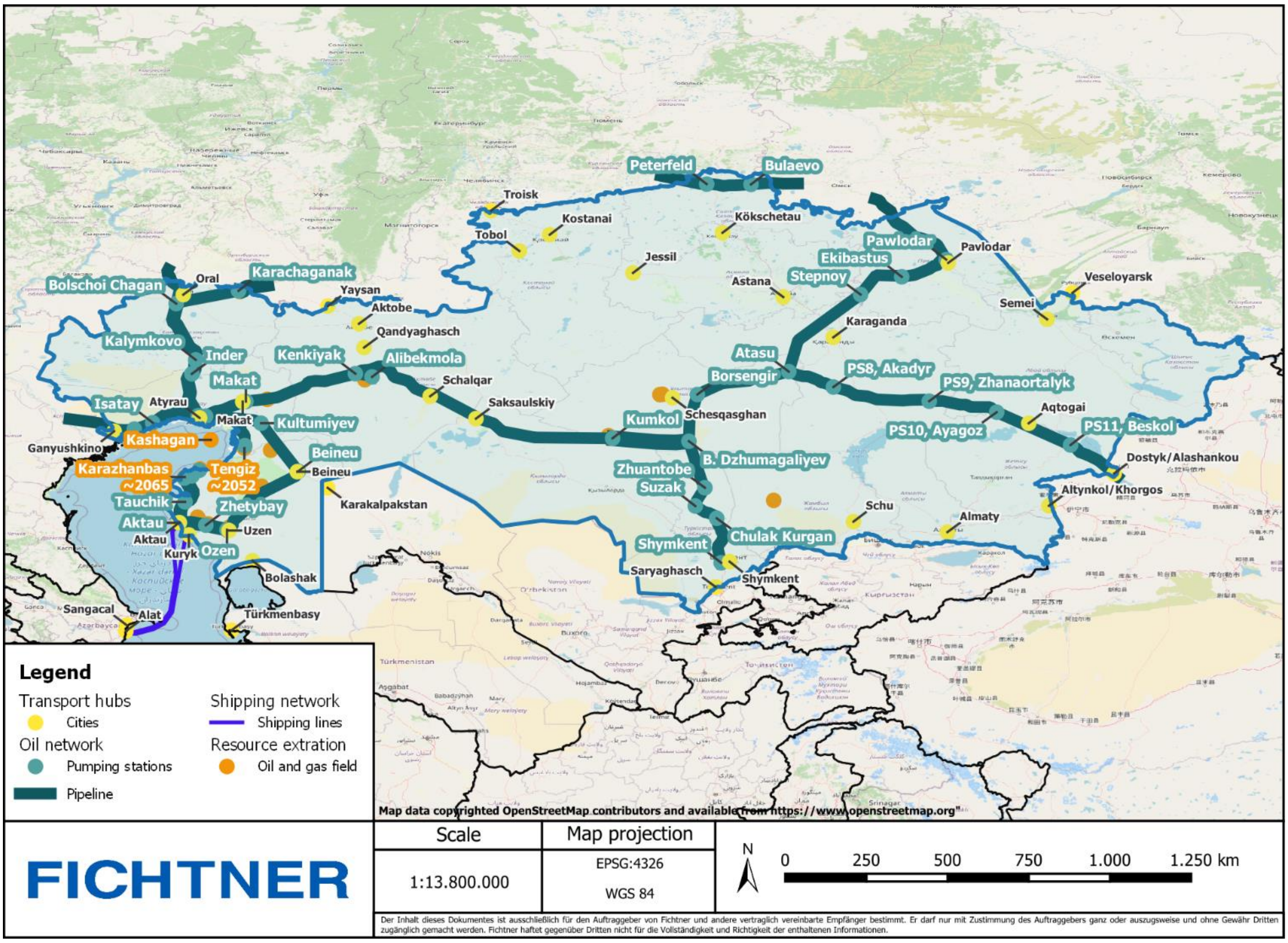

Figure 7: Kazakh main oil network

2.2.2 Production

The production of oil accounts for appr. 50% of domestic energy production in Kazakhstan [1]. In 2022 81.7 Mt crude oil and 2.5 Mt gas condensate was produced. The main production sites which are responsible for the largest share of oil output in Kazakhstan (around 63%) are as already for the gas the so-called "big three", namely

- Tengiz (on-shore) 35%,
- Kashagan (off-shore) 15% and
- Karachaganak (on-shore gas condensate field) 13%.

The oil production will increase in the following years. One reason is the growing oil reserves through exploration. By 2031 it is expected that KMG JSC alone wants to have discovered 299 Mt new oil reserves. For 2023 the Kazakh Ministry of Energy forecasts an oil output of 90.5 Mt. [15] Oil production is expected to increase up to 101 Mt by 2030 [1].

2.2.3 Transmission Network

The oil pipeline network infrastructure of Kazakhstan in total amounts to 7,988.2 km of pipelines [6]. KazTransOil JSC owns and operates most of the Kazakh pipelines. 5,373 km pipelines belong to this company. In 2022 40.6 Mt of oil were transported through this network. 44% of the transport volume were transmitted for the domestic market, 31% for export and 25% for transit. [15]

The Kazakhstan-China Pipeline LLP owns two pipeline segments. The operation and maintenance are provided by KazTransOil JSC. Kazakh oil and Russian transit oil are transported through these pipelines to China and to supply the domestic market. The oil transport amounted 19.2 Mt of crude oil in 2022 and consist of 25% transit oil from Russia, 41% oil for the domestic market and 7% export oil for China. [15]

The Caspian Pipeline Consortium is partial owner and operator of a single oil pipeline connecting Kazakhstan and Russia. The pipeline is likewise operated by KazTransOil JSC. As a cooperation of Kazakhstan, Russia and leading companies of the crude oil sector this pipeline was constructed as the primary export route for Kazakh crude oil. All the transmitted 58.7 Mt oil in 2022 were exported to Russia and further countries in Europe. [15]

MunaiTas LLP is the owner of a pipeline section connecting the oil assets at the Caspian Sea and the middle of Kazakhstan as well as connecting further pipelines heading east. Operating service is provided by KazTransOil JSC. In 2022 5.6 Mt oil were transported through the pipeline, 79% of that for the domestic market and 21% for export. [15]

Karachaganak Petroleum Operating B.V. is operator of the Karachaganak oil and gas field and owner of a pipeline connection from the oil and gas field to the main pipelines for oil export like the Caspian Pipeline. [28]

Table 2 shows the design of the main oil pipeline sections of Kazakhstan in order of the pipeline owners.

Table 2: Main oil pipeline sections in Kazakhstan

Pipeline owner/ pipeline section	Length [km]	Capacity [Mtpa]	Diameter [mm]	Number of strands
KazTransOil JSC				
Uzen-Atyrau-Samara pipeline	683/540 [17]	40/17 [17]	1,000/700 [17]	1 [16]
Pavlodar-Shymkent pipeline	1,640 [19]	22 [21]	800 [20]	1 [19]

Pipeline owner/ pipeline section	Length [km]	Capacity [Mtpa]	Diameter [mm]	Number of strands
Kumkol-Karakoin pipeline	230/230/199 [19, 21]	20 (all together) [22]	500/700/800 [19, 21]	3 [22]
Ozen-Zhetybay-Aktau pipeline	112/141 [17]	17 (both together) [17]	500/700 [17]	2 [17]
Kalamkas-Karazhanbas-Aktau pipeline	202/290 [17, 18]	15 (both together) [17]	700/500 [18]	2 [17]
Omsk-Pavlodar pipeline	200 [16]	45 [21]	800 [21]	1 [21]
Kazakhstan-China Pipeline LLP				
Kenkiyak-Kumkol pipeline	794 [23]	20 [23]	813 [23]	1 [23]
Atasu-Alashankou pipeline	965 [24]	20 [24]	813 [24]	1 [24]
Caspian Pipeline Consortium				
Caspian Pipeline	450 [25]	72.5 [26]	1016/1066 [25]	1 [25]
MunaiTas LLP				
Kenkiyak-Atyrau pipeline	455 [27]	6 [27]	600 [27]	1 [27]
Karachaganak Petroleum Operating B.V.				
Karachaganak-Atyrau pipeline	650 [28]	7 [28]	600 [28]	1 [28]

Besides oil transportation by pipeline Kazakhstan diversified the export opportunities through sea transportation.

In 2022 the Kazakh government and the “State Oil Company of the Republic of Azerbaijan” (Socar) signed an agreement for the shipment of 1.5 Mt oil per year from Aktau to Baku (Alat) [15]. In total 2.1 Mt oil were transported from Aktau to ports in the Caspian Sea like Sangachal and Alat in Azerbaijan and Machatschkala and Astrakhan in Russia [30]. Active transport ship operators are NMSC Kazmortransflot LLP (Kazakhstan), Mobilex (Kazakhstan), CJSC Azerbaijan Caspian Shipping Company (Azerbaijan), Socar Logistics DMCC (Azerbaijan), Arrow Star (Türkiye), Navigator (Russia) and Eurasian Trading (Dubai) [31].

2.2.4 Export

In 2022 Kazakhstan exported 64.3 Mt of crude oil according to KMG JSC. This amounts approx. 76% of domestic oil production. In 2023 it is expected that the exports increase up to 71 Mt [15].

Main markets are Europe (70-80% of 68.5 Mt export volume in 2020), South-East-Asia, as well as the United States of America. Most exports are delivered via pipelines [1, 16]. Important export routes are:

- The Caspian Pipeline (CP) via Russia in the West to Novorossiysk on Russia's Black Sea coast with a capacity of 83 Mt per annum (72.5 Mt Kazakh section), also carrying Russian oil (up to 10%) along the route [1, 15].
- The Atyrau-Samara pipeline via Russia as part of the Transneft System, accounting for 25% of the total oil exports [1].
- The Atasu-Alashankou pipeline connection to China which holds a theoretical capacity of 20 Mt per annum but is limited by the capacity of the section between Kenkiyak and Atyrau. Actual quantities in recent years accounted for only 0.5 Mt (2020) and 1 Mt (2020) including Russian crude oil which is also transported to China. [1]
- In addition to the above-described on-shore export routes, multimodal route is used for the transport of Kazakh oil to Europe, staring in the port of Aktau. From here oil is shipped to the port of Baku across the Caspian Sea. From Baku the oil is injected into the Baku-Tbilisi-Ceyhan pipeline which ends on the Turkish coast of the Mediterranean Sea at Ceyhan crossing the countries Azerbaijan and Georgia along its route. Only half of the capacity of this pipeline was used in 2021. In the same year Türkiye has raised the transit fees 3-4-fold, making this route less economically attractive. [1]

2.2.5 Import

Kazakhstan is a large net exporter of oil, however, minor volumes from Russia via pipelines are imported [1]. Imports of oil used in Kazakhstan amounted up to 190,000 $ in oil in 2021 which was sourced from Russia [29]. Besides this insignificantly low import value for the domestic market Kazakh pipelines are used for oil transit as described in the transport network section above. In 2022 around 10 Mt Russian oil were transmitted through the Omsk-Pavlodar pipeline to Kazakhstan and were further transferred to China via the Atasu-Alashankou pipeline. [16]

2.3 Kazakh Railway Network

2.3.1 General Remarks

“Kazakhstan Temir Zholy JSC” (KTZ JSC) is a Kazakh transport and logistic holding company. Sole shareholder of the company is the national welfare fund “Samruk-Kazyna JSC”. The KTZ JSC holding consists of 26 subsidiary companies. These perform tasks for parts of the network. For instance, the subsidiary “KTZ- Freight Transportation LLP” is in charge of the freight transport. As general operator of the main railway network the KTZ JSC holding is responsible for the passenger and freight transport and service as well as for the management and maintenance of the railway infrastructure. Ownership of the railway infrastructure belongs to the state just like 50% of the rolling stock including almost all locomotives. [2, 3]

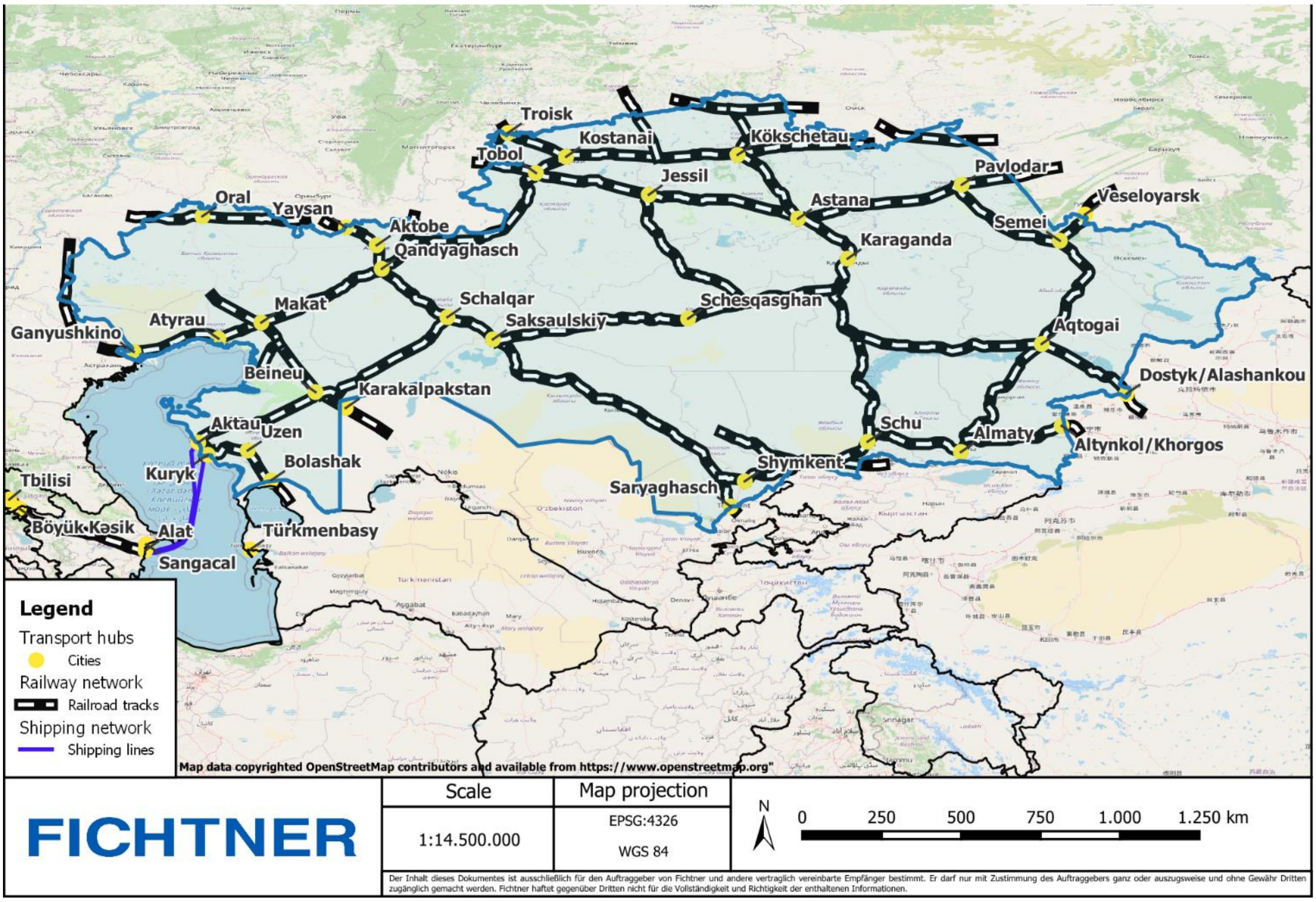

Figure 8: Kazakh main railway network

2.3.2 Railway network

The length of the operating main railway network totals around 16,000 km [3]. 4,900 km (2017) of the railway network are built as double tracks. 4,200 km (2017) are electrified railway tracks. [2, 5] The gauge of the railway tracks is the Russian standard gauge 1,520 mm which is usual for former Soviet Union countries and therefore for all neighboring countries except for China (1,435 mm) [4].

Figure 8 shows the main railway network of Kazakhstan. For international land transport from European states to China and vice versa or between neighboring countries of Kazakhstan especially Russia and China, Kazakhstan is of importance as a transit corridor. The relevance is shown by the “Central Asia Regional Economic Cooperation” (CAREC) which is a partnership of 11 countries of the Central Asian region including Kazakhstan with the target of economic growth and development of the transport infrastructure. [7]

Similar targets are followed by the European Union funded project “Transport Corridor Europe-Caucasus-Asia” (TRACECA) and the association “Trans-Caspian International Transport Route” (TITR, Middle Corridor) [13]. CAREC focuses in part on 6 railway corridors. Kazakh railway border crossings important for CAREC are thereby at Ganyushkino, Troisk, Yaysan and Veseloyarsk at the Russian border, Alashankou and Khorgos at the Chinese border, Saryaghasch and Karakalpakstan at the Uzbek border and Bolashak at the Turkmen border. [8]

Furthermore, an existing transport route via ferries across the Caspian Sea is part of the corridors of CAREC, TRACECA and in particular TITR [13]. The ports of Aktau and Kuryk in Kazakhstan are connected by a shipping line to Alat in Azerbaijan. Especially the port in Aktau needs to be modernized and expanded to improve the throughput of goods as well as the Kazakh railway network which is also often outdated and in need of expansion or maintenance [10]. Freight at the port can be loaded and transported by roll-on/roll-off principle loading up to 35 heavy trucks on the ferry. There is also an oil terminal, a grain terminal and railway ferries that can carry up to 54 rail wagons which are moved directly onto the ferry’s rail tracks via tracks at the berth. [9, 11, 12]

2.3.3 Rolling Stock and international Transport of Goods

The number of rolling stocks includes 1,800 locomotives, 46,200 freight wagons owned only by KTZ JSC, about 75,000 fright wagons owned by other private companies (2017) and 2,400 passenger wagons [2]. It needs around 5 days for a turnover of a working freight wagon. The average traffic speed on Kazakh railway tracks is approximately 44 km/h. That’s related to the high-capacity utilization in the range of 70-100% due to the large number of single-tracks. Therefore, the possibility of additional freight carried by trains is limited. [5]

Railway fright transport plays the most important role in the Kazakh transport system for international and domestic transportation [5]. In 2021 410.3 Mt cargo was transported by the Kazakh railway. A share of 50.7 million tons were exported to Russia and Kyrgyzstan which are countries of the Eurasian Economic Union (EAEU) and 36.3 million tons to non-EAEU countries such as China. The import amount from EAEU countries is 14.2 million tons while the import from non-EAEU countries is 37.4 million tons. 22.1 million tons were transit cargo which was transported only for passage in Kazakhstan. The largest share of railway transport belongs to the inland transport of cargo with a total of 249.6 million tons. [6]

The transport performance of Kazakhstan in 2021 comes up to 297.4 billion ton-kilometers (tkm). Inland transport has the largest share with 120.7 billion tkm followed by export with 86.6 billion tkm.

Russia and China are the most important trading partners for import and export. Exports to Russia are mostly ores, oil and ferrous metals while China additionally imports coal. Approximately 75% of the monetary export value and approximately 35% of the monetary import value of the trade with Russia are transported by railway. [6]

The main goods transported by railway in 2021 are the following illustrated by Figure 9.

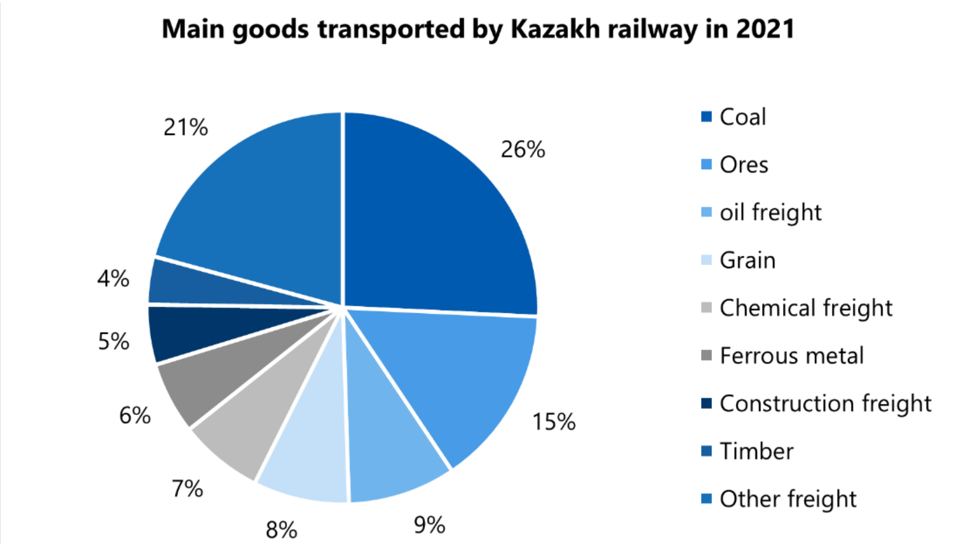

Figure 9: Main goods transported by Kazakh railway in 2021 [3]

3 Hydrogen Transport - a Literature Review

With regards to future green and large-scale H_2 transport a large number of studies have been published so far, in which different transport options are described and compared. A selection of reports from different organizations were suggested by the client to be reviewed to provide an overview of transport-associated cost figures.

3.1 Transport Studies

In the following the main take ways of each of the provided transport studies are summarized.

3.1.1 #1 European Hydrogen Backbone

Published by EHB initiative and Guidehouse (2020).

Take Aways

- Initiative of multiple European gas companies (mainly TSOs), sketching a H_2 network agenda across Europe to supply demand-clusters in the center of the continent from production and import areas in the North, South and East.
- The future H_2 network (i.e. European Hydrogen Backbone (EHB)) is based for the largest part on repurposed transmission pipelines for natural gas, which represents a very cost-effective way for large-scale H_2 transport even over long distances.
- Pipeline capacities of existing infrastructure for natural gas will not be fully exploited in a hydrogen scenario in order to keep costs for compressor stations low and hence provide for a more cost-effective transport system.

Relevance for transport assessment

- Figures on indicative cost estimates for H_2 pipeline transport (new and repurposed). The given cost ranges are assumed to be representative of the EU-average.
- Provides a comprehensive summary of critical aspects of a H_2 pipeline network in Europe. Especially with regards to repurposing existing natural gas infrastructure the publications of the EHB initiative embody a valuable and accessible reference for pipeline transport analyses on a concept level.

3.1.2 #2 dena-Leitstudie - Aufbruch Klimaneutralität

Translated into English as ‚The dawn of climate neutrality‘
Published by Deutsche Energie-Agentur GmbH (dena) (2021).

Take Aways

- Ambitious targets for climate-neutral Germany require a diversified energy system, large investments, strong partnerships and respective framework conditions.
- Central aspects for this undertaking from a technological point of view are:
  - increased energy efficiency in every sector (especially industry and heating of buildings),
  - direct use of renewable energies and the wide electrification of energy consumers,
  - broad application of so-called power fuels, i.e. gaseous and liquid energy carrier,
  - natural and installed CO_2 sinks (CCS/ CCU).
- H_2 is considered a critical energy carrier in the future carbon-neutral energy system in Germany with an ever-growing share in the energy mix from 2030 onwards.

Relevance for transport assessment

- The study mainly focuses on absolute numbers of energy demand and proposes a mix of different technologies to meet the set climate targets in Germany.
- The aspect of H_2 import origins and associated transport options are not discussed which is why this study is not considered relevant for the transport assessment.

3.1.3 #3 Middle Corridor - Asian Development Bank Institute

Published by the Asian Development Bank Institute (ADBI) (2021).

Take Aways

- Strategic relevance of the Middle Corridor for China which heavily subsidizes its use.
- Established but inefficient trans-continental rail system for containerized trade connecting China, Central Asia, Caucasus, Türkiye and Europe.
- Very low trade volumes between Middle-Corridor countries and the European Union despite policy goals for development and regional engagement.
- Several physical and geographic bottlenecks along the route which limit trade flow.

Relevance for transport assessment

- figures on trade volumes and values between China and Europe.
- figures on freight rates.
- route description of existing rail system via the Middle-Corridor countries between China and Europe, including the identification of bottlenecks.

3.1.4 #4 No-regret hydrogen - Charting early steps for H_2 infrastructure in Europe

Published by Agora Energiewende (2021).

Take Aways

- Identification of so-called 'no-regret' H_2 infrastructure areas across Europe along the H_2 value chain covering production, transport, storage, distribution and off-take.
- 'No-regret' approach based on
  - demand-clusters with sectors and industrial off-takers that are considered to be decarbonized most easily through H_2 applications (e.g. chemical industry, steel production, maritime shipping),
  - promising future availability of H_2 pipeline networks to connect production sites, storage facilities and end-consumers,
  - potential storage sites (e.g. salt caverns, existing cavern storages for natural gas),
  - H_2 production potential in Europe and the North Africa Middle East (MENA) region, both in a scenario of purely RE-based H_2 production (i.e. electrolysis) as well as a scenario considering steam-methane-reformation (SMR) with carbon capture and storage (CCS).
- Uncertainty of the relevance for sea-borne transport option (i.e. LH_2 and NH_3) on a European scale, as the model used is restricted to Europe and North Africa. Hence, potential sea-borne flows on a global scale are considered.

Relevance for transport assessment

- Collection of cost estimate figures drawn from various studies:
  - transport costs via pipeline (new and repurposed),
  - conversion costs (H_2 to NH_3, NH_3 to H_2, H_2 to LH_2, LH_2 to H_2),
  - sea-borne transport costs considering several transport routes between Europe and Saudi- Arabia (LH_2 and NH_3).
- Identification of a 'no-regret' route in South-East Europe close to the Black Sea on Romanian territory as well as on the border between Türkiye and Bulgaria. Those locations can be of relevance when identifying final import points at the end of the analyzed transport route between Kazakhstan and East-Europe.

3.1.5 #5 Ariadne-Analyse - Wasserstoffimportsicherheit für Deutschland

Translated into English as ‚Hydrogen import security for Germany‘
Published by Kopernikus-Projekt Ariadne Potsdam-Institut für Klimaafolgenforschung (PIK) (2021).

Take Aways

- Energy imports in Germany will successively decline in absolute numbers over the years, which is mainly due to increased energy efficiency, electrification and the phase-out of fossil fuels.

- On the other hand, the import of climate-neutral energy carriers such as H_2 and other PtX[2] products will increase substantially between the target years 2030 and 2045.
- The security of H_2 supply through imports can be fostered via
  - measures for early risk-detection,
  - diversified import origins,
  - import cooperations and partnerships.

Relevance for transport assessment

- The study focuses on the projection of future H_2 import demand in Germany, as well as outlining different H_2 import-associated risks and strategies to both mitigate the vulnerability of potential H_2 supply interruptions and foster H_2 import security.
- The aspect of H_2 import origins and associated transport options are not discussed from a technical point of view which is why this study is not considered relevant for the transport assessment.

3.1.6 #6 Kosten von grünem Wasserstoff Import via Pipelines

Translated into English as ‚Costs of green hydrogen import via pipelines‘
Published by Frontier Economics (2021).

Take Aways

- Cost analysis of H_2 import to Germany from two areas of origin, i.e.
  - North Africa,
  - Ukraine.
- Two transport options have been assessed. For H_2 imports from North Africa both shipping (German port Hamburg) and pipeline transmission were analyzed. H_2 imports from Ukraine were assumed exclusively via transmission pipelines (no shipping).
- H_2 transportation costs have critical impact on overall costs of landed H_2. In some scenarios low transportation costs compensate high production costs. E.g. H_2 imports from Ukraine might be cheaper compared to North Africa, despite higher production costs and due to shorter transport distances via large pipelines.
- H_2 transport via shipping embodies a more cost-effective option for transport volumes of lower magnitude in comparison to new built pipeline systems.
- In case existing natural gas infrastructure can be repurposed for the dedicated transport of H_2, pipeline transmission embodies the most economic transport option for transport volumes of higher magnitude. However, the H_2-readyness as well as availability of pipelines of large diameters would be a pre-requisite for realization and must be assessed case by case.

[2] PtX (Power-to-X) refers to technology applied to produce synthetic energy carriers, e.g. hydrogen using electricity as an energy source and other chemical inputs (e.g. water electrolysis for hydrogen production)

- The availability of dedicated H_2 pipeline transmission systems (repurposed or new) is expected earliest in 2030. Accordingly, shipping is more promising in the short-term due to partly existing terminals at port side for NH_3 as well as higher flexibility regarding the global points for H_2 import and export, depending on available supply and demand.
- Longer distances in the case of shipping does not show as high of an impact as it does in the case of pipeline transmission. The costs for conversion of H_2 to NH_3 embody the largest share of transport costs via shipping. On the other hand for pipeline transmission longer distances require more compression works and obviously longer pipeline distances, which directly increase associated transport costs.

Relevance for transport assessment

- Cost figures for pipeline transmission of new and repurposed infrastructure.
- Cost figures of H_2 production in the countries of origin which might provide a basis for assumed production costs in Kazakhstan. Cost figures for Ukraine derive from assumption of mainly on- shore wind power production.
- Costs for shipping were drawn from an IEA report[3].

3.1.7 #7 Global Hydrogen Review 2022

Published by International Energy Association (IEA), CleanEnergy Ministerial, HydrogenInitiative (2022).

Take Aways

- Extensive overview of current developments in the hydrogen sector globally, reviewing state-of-the-art and anticipated developments from a value chain perspective, as well as trade and policy implications for a future green H_2 economy.
- On a global scale off-take agreements fall short when compared to export ambitions due current uncertainties related to regulation and policies. Especially the low policy activities are identified to inhibit the creation of long-term demand and hence, more incentives must be implemented (e.g. through policies) to facilitate final investment decisions in favour of H_2 off-take.
- Shipping of NH_3 in most projects identified as preferred transport option. With regards to re-purposing import terminal infrastructure, rededicating LNG terminals for NH_3 seem to be more feasible when compared to LH_2 under both economic and technical aspects.
- Repurposing natural gas pipelines for H_2 transport is considered a cost-effective way to implement future H_2 transmission networks.

Relevance for transport assessment

- Cost figures for pipeline transmission of new and repurposed infrastructure, as well as NH_3 and LH_2 shipping drawn from gas4climate-report[4].

[3] IEA (2019) The Future of Hydrogen [56]
[4] EHB#2_report_part1_210614.indd (gasforclimate2050.eu)

- Cost figures on transport.
- Energy demand figures for conversion to LH_2, as well as published projects for LH_2 tankers and respective transport capacities.

3.1.8 #9 HySupply A Meta-Analysis towards a German-Australian Supply-Chain for Renewable Hydrogen

Published by the National Academy of Science and Engineering (acatech) and the Federation of German Industries (BDI).

Take Aways

- Analysis of a H_2 supply-chain partnership between the producer country Australia and the off-take country Germany regarding future delivery and off-take potentials.
- Australia as a country with large potential for RE and hence H_2 production is considered a key partner country for Germany that shows a large import demand for H_2 in the future in order to decarbonize its economy.
- Long-distance transport from Australia to Germany technically feasible through shipping various H_2 carriers.
- Comparison by literature review of several H_2 carriers focus on conversion, storage, shipping and re-conversion of feasible options:
  - Liquid hydrogen (LH_2),
  - Liquid organic hydrogen carriers (LOHC),
  - green NH_3,
  - green methanol.

Relevance for transport assessment

- Figures of CAPEX/ OPEX, energy demand and efficiency of conversion, storage, shipping and re-conversion of LH_2 and NH_3 based on meta-analysis of relevant literature.
- Provides a comprehensive, yet brief summary of the multiple H_2 carrier options with regards to transportability via ships, technical implications and technology readiness level (TRL).

3.2 Summary of Transport Cost Figures

In Table 3 transport-associated cost figures which were provided in the respective transport-studies are shown.

Table 3: Overview transport cost figures

#	Study publisher	H_2 carrier type	Transport option	Cost figures	Unit
1	EHB	H_2	Pipeline (EHB 75% retrofitted)	0.09-0.17	EUR/kg/1,000 km
		H_2	Pipeline (100% new infrastructure)	0.16-0.23	EUR/kg/1,000 km
		H_2	Pipeline (100% repurposed infrastructure)	0.07-0.15	EUR/kg/1,000 km
2	dena	H_2 and derivatives	-	-	-
3	ADBI	Freight container wagon (no carrier type specified)	Train and ship	1,358-2,333	USD/ (20 ft/<24 t - 40 ft/<=28 t) from Khorgos to Port Baku via Port Aktau
		Freight container wagon (no carrier type specified)	Train and ship	1,584-2,656	USD/ (20 ft/<24 t - 40 ft/<=28 t) from Khorgos to Port Poti via Port Aktau
		Freight container wagon (no carrier type specified)	Train and ship	1,591-2,661	USD/ (20 ft/<24 t - 40 ft/<=28 t) from Khorgos to Port Batumi via Port Aktau
		Freight container wagon (no carrier type specified)	Train and ship	2,363-3,634	USD/ (20 ft/<24 t - 40 ft/<=28 t) from Khorgos to Istanbul via Port Aktau

#	Study publisher	H_2 carrier type	Transport option	Cost figures	Unit
4	Agora[5]	H_2	New pipeline	9.168 (0.6596)	EURct/kg/139 km (EUR/kg/1,000km)
		H_2	Repurposed pipeline	2.024 (0.1461)	EURct/kg/139 km (EUR/kg/1,000km)
		LH_2/NH_3	Ship	0.807 (without conversion cost) (0.0581)	EURct/kg/139 km (EUR/kg/1,000km)
5	Ariadne	-	-	-	-
6	Frontier economics	H_2	New pipeline (48-inches)	0.58 – 1.14 (0.22 - 0.44)	EUR/kg/2,610 km EUR/kg/1,000km
		H_2	Repurposed pipeline (48-inches)	0.33 – 0.79 (0.13 - 0.30)	EUR/kg/2,610 km (EUR/kg/1,000km)
		H_2	New pipeline (24-inches)	1.46 – 2.89 (0.56 - 1.12)	EUR/kg/2,610 km (EUR/kg/1,000km)
		H_2	New pipeline (12-inches)	2.26 – 4.46 (0.87 - 1.71)	EUR/kg/2,610 km (EUR/kg/1,000km)
		LH_2[6]	Ship	Approx. 1.33-2.3	EUR/kg/Agadir-Hamburg[7]
7	IEA[8]	H_2	New pipeline (20-inches)	Approx. 0.92-2.71	USD/kg/1,000 km
		H_2	Repurposed pipeline (20-inches)	Approx. 0.22-0.59	USD/kg/1,000 km

[5] Transport distance given by a hexagon with a size of 50,000 km² - transport costs are calculated for the distance from the edge to the center (half hexagon) which accounts for approx. 139 km
[6] Cost figures approximated from a graph
[7] No distance indicated. The calculation is based on results of a report by the IEA in 2019 “The Future of Hydrogen” [56]
[8] Cost figures approximated from a graph

#	Study publisher	H_2 **carrier type**	**Transport option**	**Cost figures**	**Unit**
			New pipeline (48-inches)	Approx. 0.18-0.35	USD/kg/1,000 km
			Repurposed pipeline (48-inches)	Approx. 0.08	USD/kg/1,000 km
		LH_2	Ship	Approx. 2.4	USD/kg/1,000 km
		NH_3	Ship	Approx. 1.98	USD/kg/1,000 km
		LOHC	Ship	Approx. 2.03	USD/kg/1,000 km
9	HySupply[9]	LH_2	Ship	108-451 (CAPEX for shipping)	EUR/t/20.000km
		NH_3[10]	Ship	Approx. 40-119 (CAPEX for shipping)	EUR/t/20.000km
		LOHC	Ship	Approx. 43-82 (CAPEX for shipping)	EUR/t/20.000km
		Methanol[8]	Ship	Approx. 24-193 (CAPEX for shipping)	EUR/t/20.000km

[9] Cost figures are given for CAPEX and fixed OPEX. Additional figures are provided for the energy demand. However, levelized cost figures which would be more comparable to the figures of other studies are not provided in the report.
[10] cost figures in the cases of NH3 and methanol account for associated CAPEX costs per mass unit of H2-equivalent

3.3 Remarks by Fichtner

Quantifying costs for hydrogen transport of future transport options is a complex undertaking, as numerous assumptions (variables) have to be made for the cost calculation. Those variables show varying degrees of influence on the final results. Depending on the needed level of accuracy of the cost calculation, some calculation approaches consider more variables than others and accordingly, an accurate comparison between transport cost figures of different sources can only be done if the taken calculation approaches and all assumptions made are provided in a transparent way to the reader.

After reviewing the above-mentioned transport-studies it becomes evident, that the level of transparency varies between the studies. Accordingly, the listed cost figures of the studies in Table 3 must be regarded with caution.

For the following transport assessment Fichtner will therefore make use of in-house calculation tools, both for shipping and pipeline transmission. An exception is made for the study by the European Hydrogen Backbone (EHB). Here an extensive framework for future pipeline transmission concepts is provided, based on the expertise of a number of Transmission System Operators (TSOs). Previous projects by Fichtner show that cost figures of own assessments are quite similar to the given figures published by the EHB initiative. The cost figures for levelized large-scale pipeline transport costs of H_2 by the EHB initiative will be used to assess landed costs of hydrogen via pipeline transport outside the territory of Kazakhstan. It is worth mentioning that several of the reviewed study reports make reference to the EHB initiative publications when providing pipeline-associated transport costs for H_2 transmission.

The mentioned in-house calculation tools of Fichtner are based both on literature findings and further complemented with recent market feedback that have been received in other studies of similar scope. The assumptions made will be indicated in the respective sections.

04

Hydrogen Transport - Assessment for Kazakhstan

4 Hydrogen Transport Assessment for Kazakhstan

This chapter is dedicated to suggesting potential transport options to export green H_2 or NH_3 from Kazakhstan to South-East-Europe. Critical for a techno-economic assessment is the definition of use-cases based on a number of assumptions to allow the estimation of indicative landed costs of hydrogen (LCOH).[11]

A possible transport route between Kazakhstan and South-East-Europe via the so-called Middle Corridor is indicated in Figure 10. The route is divided into several route-sections which are defined in Table 1. For the respective route section different transport options are discussed, i.e.:

- NH_3 transport via rail,
- NH_3 transport via ship,
- LH_2 transport via ship,
- (compressed) H_2 transport via pipelines,
- liquefied NH via pipelines.

For each route section one feasible alternative is chosen in order to calculate the LCOH at the end point of each route section, and ultimately at the defined import point of Europe. Also the option of using rail networks for NH_3 transport is discussed. However - as will be explained - this alternative is considered disadvantageous with regards to the expected transport volumes and the need for infrastructure development along the entire transport route to Europe when taking the Middle Corridor as defined previously.

A domestic pipeline transport assessment is dedicated for route-section 1 (from the PtX plant to the future export point within the territory of Kazakhstan), in which pipeline transmission system concepts are proposed and associated levelized costs of transport for compressed H_2 are calculated by applying an in-house pipeline optimization tool.
A different calculation approach is taken for the route sections outside the territory of Kazakhstan, using

- Cost figures of the EHB initiative (refer to section 3.1.1 and [85]) for H_2 pipeline transport.
- Cost figures for shipping of NH_3 and LH_2 derived from an in-house optimization tool for transport via ships.

[11] Cost estimates are of indicative nature according to AACE class 5 with an accuracy of +100%/ -50%.

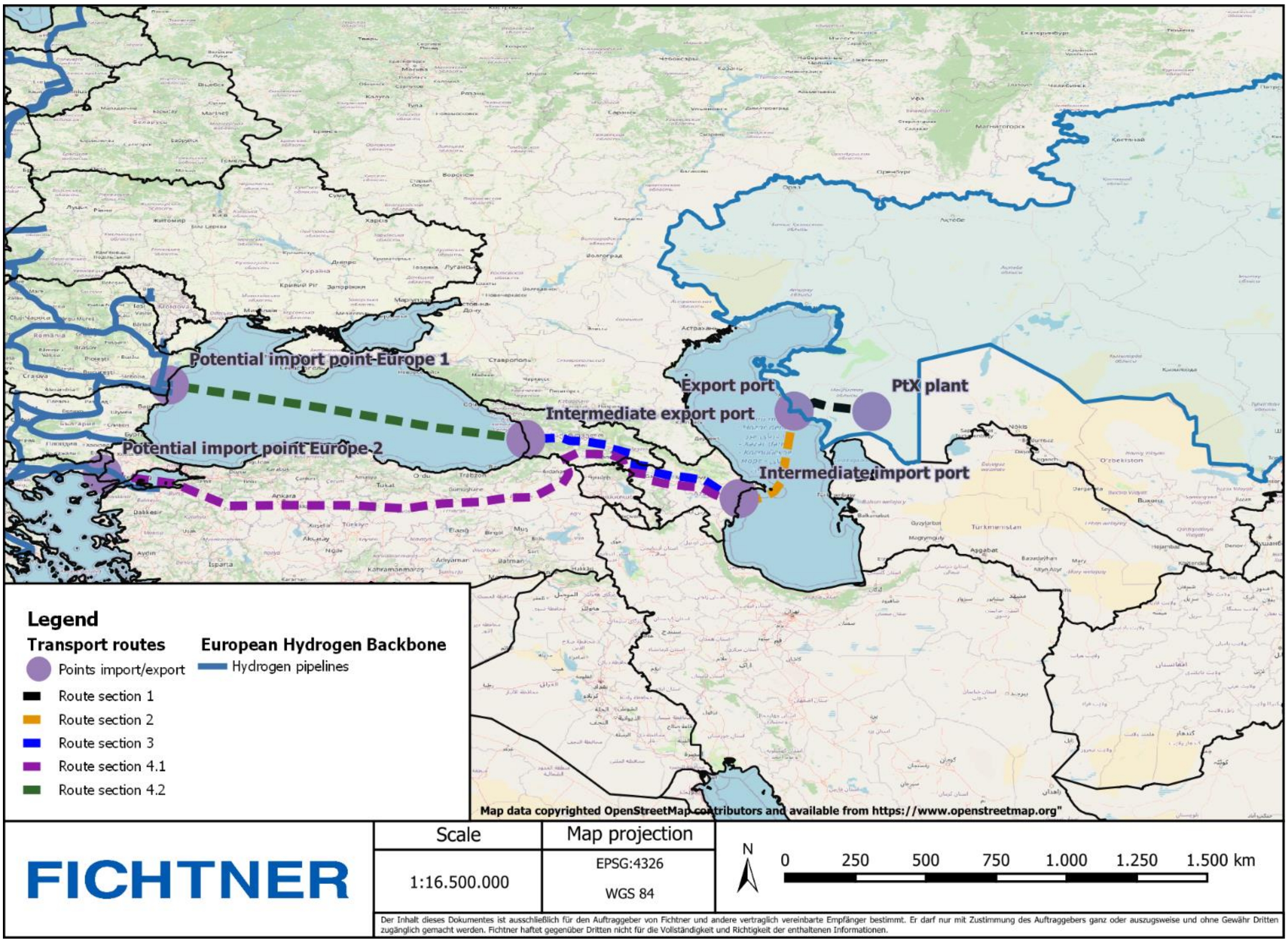

Figure 10: Transport route via the so-called Middle Corridor

4.1 Use-case Definition

Due to the high-level of the analysis, few framework conditions have been defined at the time of writing. Accordingly, the following assessment for transport options are based on a number of assumptions, which are listed in the respective sections.

Fundamental assumptions which are critical for transport-associated cost estimations for any transport option have been discussed and approved by the client. The two different cases do not represent the currently envisioned production volumes, export volumes, location of PtX plants or actual years of operation. They are to be understood as potential scenarios with a broad range of transport volumes and additional developments between the years 2030 and 2040. Two different use-cases were defined to represent a potential green H_2 and NH_3 production and export scenario in Kazakhstan for the years 2030 and 2040, respectively. It is critical to point out, that the transport assessment considers the defined transport volumes in the respective use-cases as an ultimate figure that must be understood to represent a potential transportation demand in the defined target years. Accordingly, the assessment does not take into account intermediate project developments during the scale-up phase, in which transport volumes are of much lower magnitude in the beginning and increase over time. Such scale-up use cases are not assessed in the study at hand and accordingly the findings of this study might not be applicable for a scale-up scenario.

The assumptions are listed in Table 4.

Table 4: List of assumptions for use-case definition

#	Description	Value: *Use case "Small scale" 2030*	Value: *Use case "Large scale" 2040*	Unit
1	Production goal H_2	0.18	2	Mtpa
2	Production goal NH_3	1	11	Mtpa
3	Annual full load hours	6,000	6,000	h/a
4	Electricity price	35	25	USD/MWh
5	Levelized costs of production for H_2	3.14	2.22	USD/kg
6	Levelized costs of production for NH_3	667.3	441.8	USD/t

4.2 Domestic Pipeline Transport Assessment

The goal of the system optimization is to estimate the so-called levelized costs of transport (LCOT) for H_2, based on the defined use cases with a number of assumptions and according to AACE class 5 cost estimation (accuracy +100%/-50%). For these calculations, capital expenditures (CAPEX) and operational expenses (OPEX) for new infrastructure will be considered. This requires the sizing of pipelines, as well as identifying suitable operating pressures to determine compression duties. Due to the level of analysis in this study, such calculations are subject to certain restrictions and assumptions which is explained in the following, as well as appendix 7.8.[12] Figure 11 shows the basic approach of the pipeline system optimization.

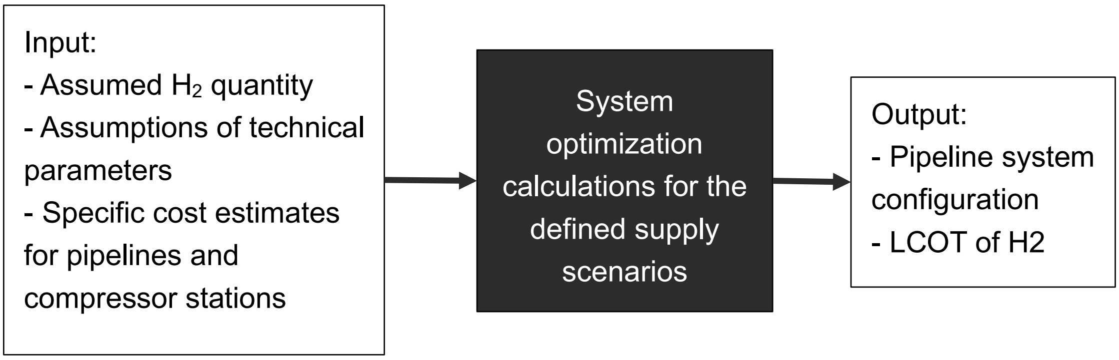

Figure 11: Basic approach for pipeline system optimization

[12] More precise cost estimations can be undertaken in a more advanced project phase when more details of the use-cases subject for evaluation are known, e.g. basic engineering phase. At such phases a pre-liminary routing corridor has already been defined and major geographic obstacles identified. In that way meters of altitude and length of the pipeline can be determined and considered when calculating compressor duties, pressure losses as well as finding sites for valves, metering and compressor stations. Such aspects will not be considered at this point of analysis.

The transport distances which are considered for such a generic assessment have been approved by the client and will be 200 km and 1,000 km respectively. With regards to the two defined use-cases for 2030 and 2040, four different pipeline transmission system concepts will be proposed. The LCOT of new systems can be compared to systems which would make use of already existing pipelines for natural gas which could potentially be repurposed for dedicated hydrogen transport.

4.2.1 System Description and Interface Matrix

Following up on the assumptions made (refer to appendix 7.8), the concept for a pipeline transmission system can be simplified as shown in Figure 12. Accordingly, Interface 1 corresponds to the starting point and Interface 2 to the end point of the pipeline route. In case an additional compressor station enhances the H_2 supply along the route, it will be positioned half-way of the pipeline route.

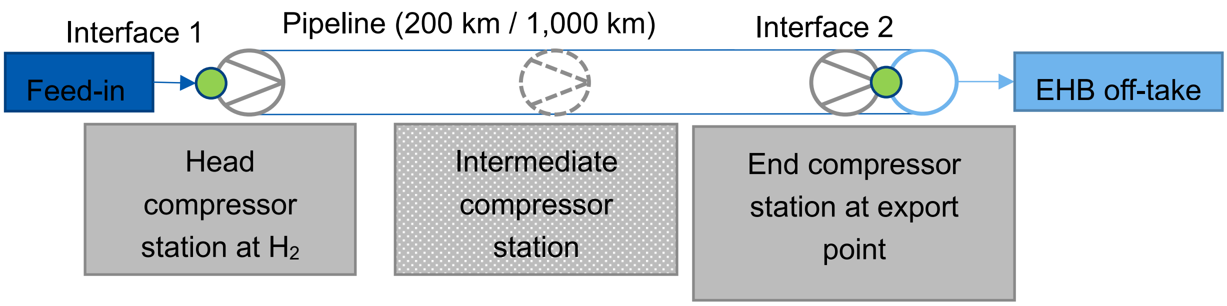

Figure 12: BFD transmission pipeline concept subject for optimization

The interfaces 1 and 2 are defined in Table 5 based on the defined use-cases and the list of assumptions.

Table 5: Interface matrix for pipeline transmission system optimization

		Interface 1		**Interface 2**	
Operating parameter	**Unit**	Compressor inlet (after H_2 production, i.e. electrolysis)		Compressor outlet at the end of the pipeline for export at Kazakh onshore border line	
		"Small scale" 2030	*"Large scale" 2040*	*"Small scale" 2030*	*"Large scale" 2040*
Pressure	**barg**	30		80	
Volume (quantity)	**Mtpa**	0.18	2	0.18	2
	t/h	30	333.33	30	333.33
Temperature	**°C**	10		10	
Gas quality	**-**	Hydrogen 5.0		Hydrogen 5.0	

The discharge pressure of the end compressor as defined in interface 2 must be regarded with caution and represents one technical set-up possibility, highly depending on the use case at hand. The value of 80 barg has been chosen according to the EHB initiatives definition of operating parameters for large pipelines. Accordingly, interface 2 could embody an export point in the event of further hydrogen transmission towards Europe via off-shore pipelines across the Caspian Sea.
On the other hand, if one assumes the production of NH_3 at export point, the required pressure at the end of the pipeline can be substantially lower, due to respective processing systems for NH_3 synthesis, e.g. 30 barg. In such cases, the need for overall hydrogen compression - and ultimately - associated LCOT would also be lower.

4.2.2 Results

Use case "Small scale" 2030 (200 km)

Table 6 and Figure 13 summarize the findings of the system optimization of a new and fictive H_2 transmission system concept for the "Small scale" 2030 use-case (200 km), based on the above defined assumptions.

Table 6: System optimization results for use-case "Small scale" 2030 (200 km)

Pipeline diameter DN	Discharge pressure head compression	Duty head compression	Discharge pressure intermediate compression	Duty intermediate compression	Duty end compression (80 barg discharge pressure s. Interface 2)	CAPEX	OPEX	LCOT
[mm]	[barg]	[MW]	[barg]	[MW]	[MW]	[Mln. USD]	[Mln. USD/a]	[USD/kgH_2]
400	100	19.7	-	-	0.5	352.2	10.2	0.24

Considering the assumed input data minimized LCOT are given for a configuration without intermediate compressor station. Discharge pressure of the head compressor station is 100 barg. This accounts for compression duty of 19.7 MW (suction pressure after electrolysis 30 barg). After pressure drop the suction pressure of the end compressor station is 78 barg, accounting for compression duty of 0.5 MW when re-compressed up to 80 barg. LCOT at 0.24 USD/kgH_2.

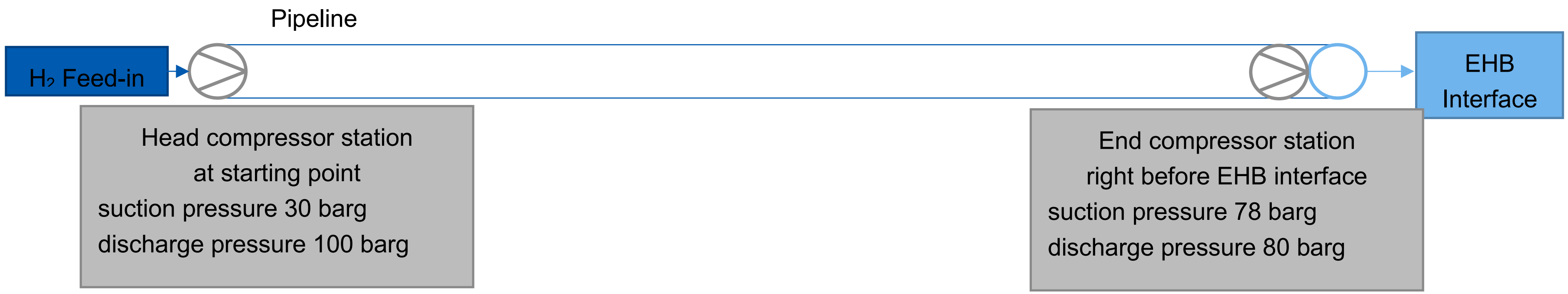

Figure 13: Simplified BFD for the use-case "Small scale" 2030 - 200 km

Use case "Small scale" 2030 (1,000 km)

Table 7 and Figure 14 and summarize the findings of the system optimization of a new and fictive H_2 transmission system concept for the "Small scale" 2030 use-case (1,000 km), based on the above defined assumptions.

Table 7: System optimization results for use-case "Small scale" 2030 (1,000 km)

Pipeline diameter DN	**Discharge pressure head compression**	**Duty head compression**	**Discharge pressure intermediate compression**	**Duty intermediate compression**	**Duty end compression (80 barg discharge pressure s. Interface 2)**	**CAPEX**	**OPEX**	**LCOT**
[mm]	[barg]	[MW]	[barg]	[MW]	[MW]	[Mln. USD]	[Mln. USD/a]	[USD/kgH_2]
500	93	18.4	93	2.5	0.1	1,594.2	23.0	0.96

Considering the assumed input data minimized LCOT are given for a configuration with intermediate compressor station. Discharge pressure of the head compressor station is 93 barg. This accounts for compression duty of 18.4 MW (suction pressure after electrolysis 30 barg). After pressure drop the suction pressure of the intermediate compressor at 500 km is 80 barg, accounting for compression duty of 2.5 MW. After pressure drop the suction pressure of the end compressor station is just below 80 barg, accounting for compression duty of 0.1 MW when re-compressed up to 80 barg. LCOT at 0.96 USD/kgH_2.

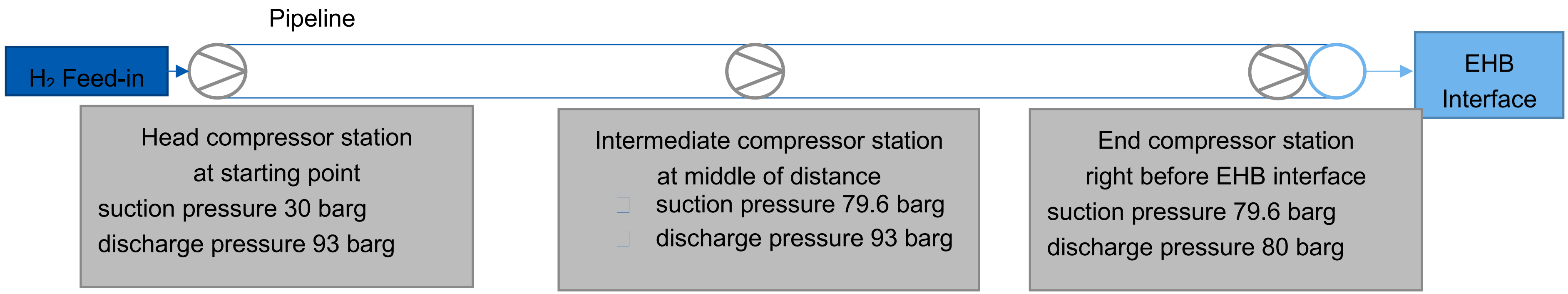

Figure 14 Simplified BFD for the use-case "Small scale" 2030 - 1,000 km

Use case “Large scale” 2040 (200 km)

Table 8 and Figure 15 summarize the findings of the system optimization of a new and fictive H_2 transmission system concept for the “Large scale” 2040 use case (200km), based on the above defined assumptions.

Table 8: System optimization results for use-case "Large scale" 2040 (200 km)

Pipeline diameter DN	**Discharge pressure head compression**	**Duty head compression**	**Discharge pressure intermediate compression**	**Duty intermediate compression**	**Duty end compression (80 barg discharge pressure s. Interface 2)**	**CAPEX**	**OPEX**	**LCOT**
[mm]	[barg]	[MW]	[barg]	[MW]	[MW]	[Mln. USD]	[Mln. USD/a]	[USD/kgH$_2$]
1200	80	175.5	-	-	17.3	1,161.2	58.5	0.08

Considering the assumed input data minimized LCOT are given for a configuration without intermediate compressor station. Discharge pressure of the head compressor station is 80 barg. This accounts for compression duty of 175.5 MW (suction pressure after electrolysis 30 barg). After pressure drop the suction pressure of the end compressor station is 72.5 barg, accounting for compression duty of 17.3 MW when re-compressed up to 80 barg. LCOT at 0.08 USD/kgH$_2$.

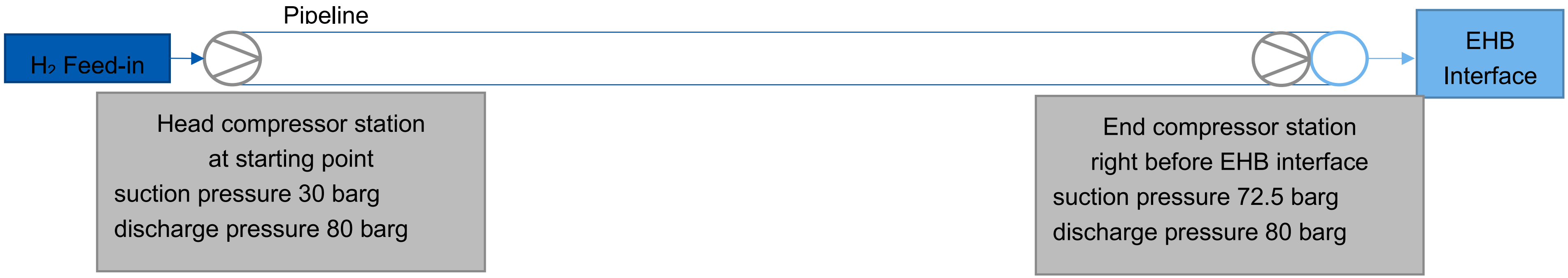

Figure 15: Simplified BFD for the use-case "Large scale" 2040 - 200 km

Use case “Large scale” 2040 (1,000 km)

Table 9 and Figure 16 summarize the findings of the system optimization of a new and fictive H_2 transmission system concept for the “Large scale” 2040 use case (1,000km), based on the above defined assumptions.

Table 9: System optimization results for use-case "Large scale" 2040 (1,000 km)

Pipeline diameter DN	**Discharge pressure head compression**	**Duty head compression**	**Discharge pressure intermediate compression**	**Duty intermediate compression**	**Duty end compression (80 barg discharge pressure s. Interface 2)**	**CAPEX**	**OPEX**	**LCOT**
[mm]	[barg]	[MW]	[barg]	[MW]	[MW]	[Mln. USD]	[Mln. USD/a]	[USD/kgH_2]
1200	95	208.2	95	34.7	3.9	3,804.3	97.6	0.23

Considering the assumed input data minimized LCOT are given for a configuration with intermediate compressor station. Discharge pressure of the head compressor station is 95 barg. This accounts for compression duty of 208.2 MW (suction pressure after electrolysis 30 barg). After pressure drop the suction pressure of the intermediate compressor at 500 km is 78 barg, accounting for compression duty of 34.7 MW. After pressure drop the suction pressure of the end compressor station is 78.3 barg, accounting for compression duty of 3.9 MW when re-compressed up to 80 barg. LCOT at 0.23 USD/kgH_2.

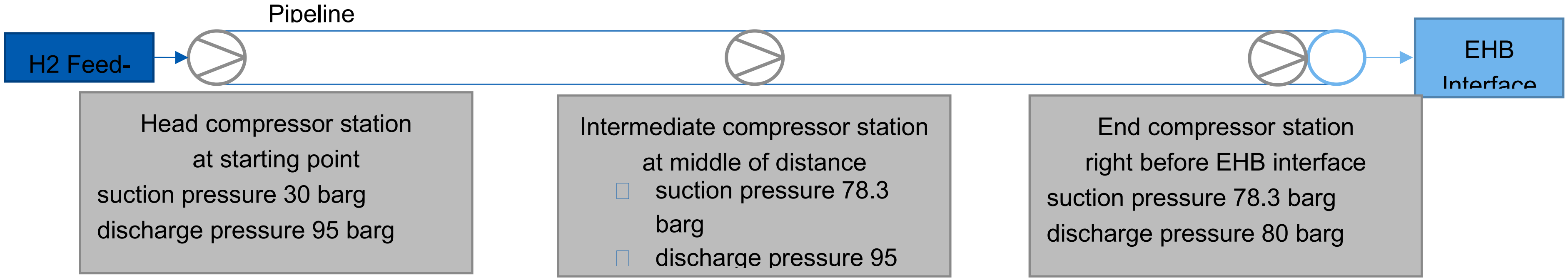

Figure 16: Simplified BFD for the use-case "Large scale" 2040 - 1,000 km

Cost split CAPEX and OPEX overview

Figure 17 and Figure 18 disclose the split of costs with regards to CAPEX and OPEX for both transport distances. It can be seen that the share of costs associated for H_2 compression increase with the transport distance, as well as with the transport volumes. Especially in the use-case “Large scale” 2040, energy demand for compression accounts for appr. 38% of total OPEX for the transport distance of 1,000 km and almost 50% of total OPEX for the transport distance of 200 km. Accordingly, operating pressures of the system should generally be kept low to allow for minimal overall compression duties of the pipeline transmission system. As already mentioned before, the operating parameters of a pipeline transmission system also depend on the end application of H_2 at the delivery point, i.e., pipeline outlet.

Another take-away of the cost split is the fact that for large transport distances, CAPEX for pipeline dominates over CAPEX for compressor units. Therefore, making use of already existing pipelines can substantially reduce transportation costs, as described in the following.

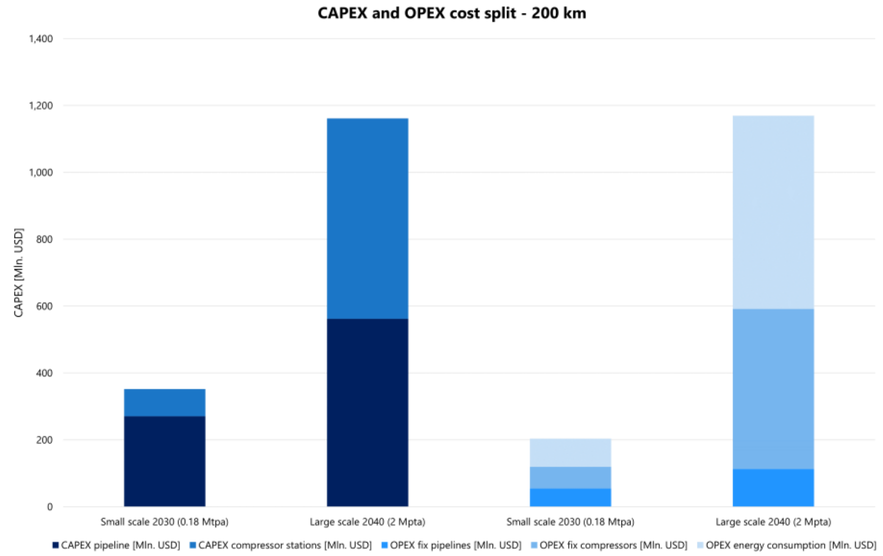

Figure 17: Cost split for a new pipeline system - 200 km

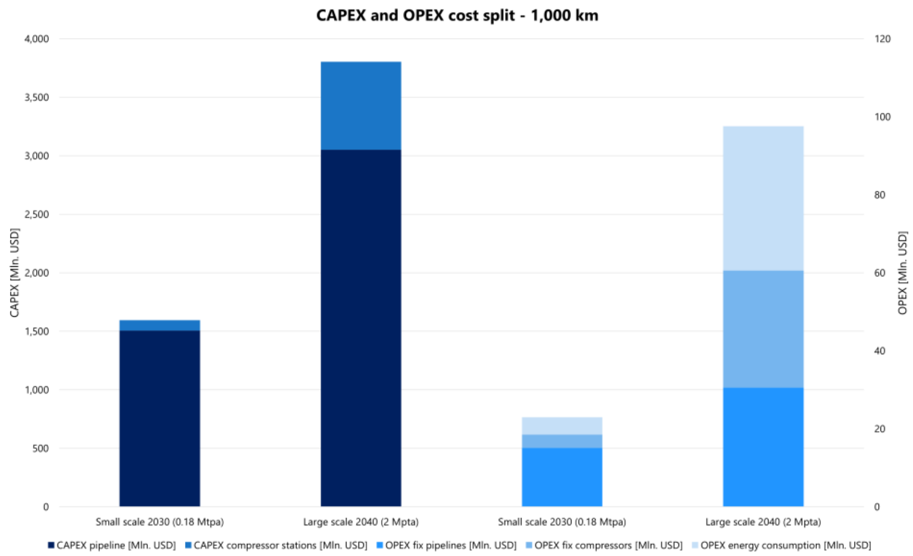

Figure 18: Cost split for a new pipeline system - 1,000 km

Potential LCOT by repurposing existing pipelines for the above-defined system concepts

Considering the idea of repurposing existing natural gas pipelines for the dedicated transport of H_2, substantial savings for the initial capital expenditures (CAPEX) can be expected. A precise forecast on CAPEX for pipeline repurposing is difficult to give at such an early stage of project analysis, as thorough investigations on the state of fitness and the physical characteristics of the respective pipeline are required. However, to the date of writing the literature and recent market feedback suggest calculating financial efforts for repurposing existing natural gas pipelines with up to 25% of the investments that would be needed for new pipelines.[13]

[13] It must be pointed out that such cost figures are only applicable if certain pre-requisites such as a H2-suitable pipeline material are met. the conservative figure of 25% represents the engineering part when looking at the split of work for new pipeline projects. Other categories are material, construction work, right of way and instrumentation.

In the case of compressor stations, it is expected that compressor units which are currently used for natural gas compression will have to be fully replaced by new compressor units, due to the different fluid properties of H_2 compared to natural gas. Accordingly, when looking at a pipeline system concept as defined above, CAPEX savings in the event of repurposing show in the share of costs for pipelines and not in compressors.

Figure 19 and Figure 20 disclose the split of costs with regards to the LCOT, both for the new systems defined above, as well as for systems which would make use of existing pipelines (repurposed "Rep"). To what degree the existing natural gas transmission infrastructure in Kazakhstan can be used highly depends on the geographic context of respective projects, the H_2-readyness of respective pipelines and the system concept for H_2 production and export.

Insights of what the repurposing of existing natural gas pipelines requires and how such an evaluation can be undertaken is explained in the appendix 7.1, based on examples in Germany.

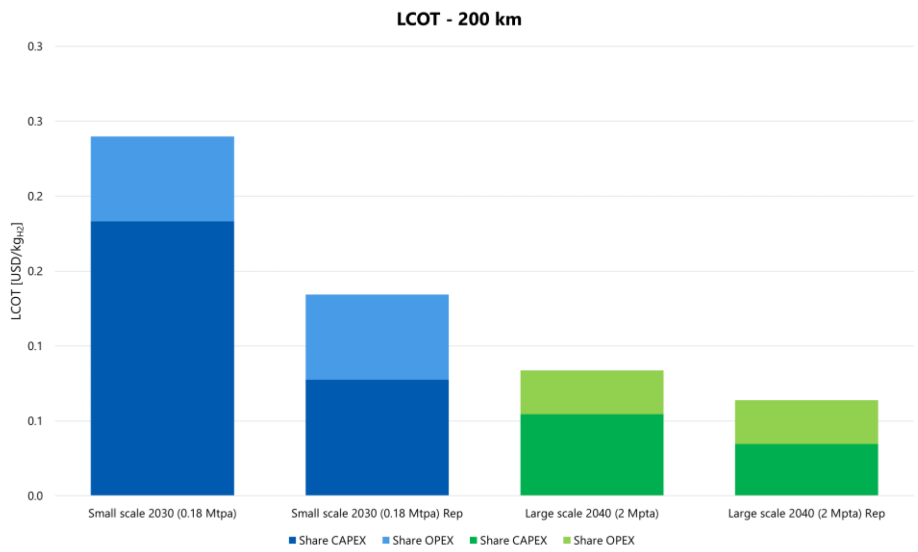

Figure 19: LCOT cost split 200 km

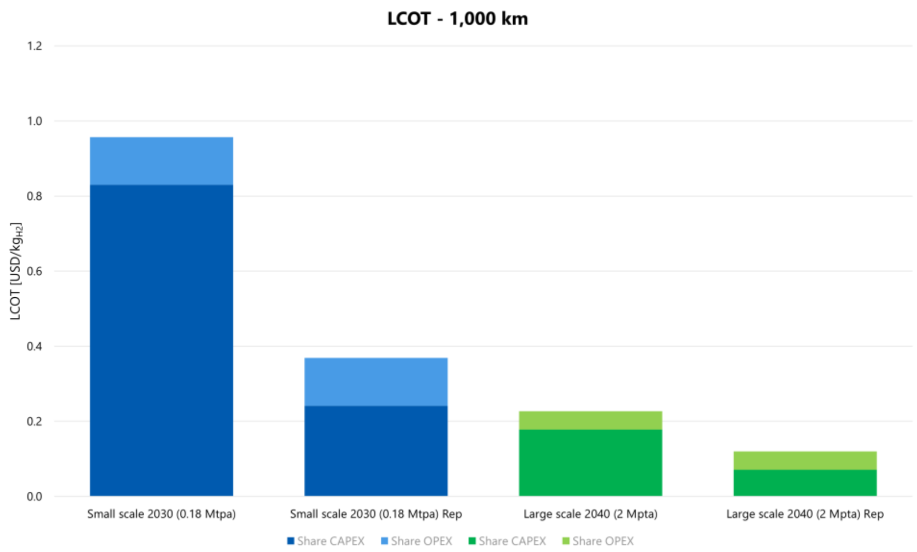

Figure 20: LCOT cost split 1,000 km

4.3 Options for Hydrogen Export via the Middle-Corridor

4.3.1 General Remarks

Since several transport options along the Middle-Corridor are assessed in this section, a distinction is introduced between two export scenarios:

- **Hydrogen export in Kazakhstan:**
  The product which leaves Kazakhstan at the designated export point on the Kazakh coast is H_2, which might be subject for processing (e.g conversion to NH_3 or LH_2) at a later stage along the route to Europe. It is assumed that the production of the H_2 takes place in the hinterlands which requires a pipeline connection from the production site to the export point.
- **Ammonia export in Kazakhstan:**
  The product which leaves Kazakhstan at the designated export point on the Kazakh coast is NH_3, which will be subject for processing (i.e. re-conversion to H_2) at the European import point at the end of the route. It is assumed that the production of NH_3 takes place in proximity to the export point. Accordingly, production costs for H_2 (as defined in section 4.1) as well as domestic transport costs via H_2 pipeline from the H_2 production site to export point (route-section 1, refer to section 4.2) must be accounted for when H_2 is converted to NH_3[14]

4.3.2 Remarks for Shipping and Rail

Rail and inland waterway transport played an important role in the former USSR due to relatively long transport distances and a cargo structure of agricultural goods and fossil fuels ideally suited to be shipped on rail. As such, there is still an integrated rail system in terms of rail gauge and signaling system in Georgia, Azerbaijan and Kazakhstan as former republics of the USSR as well as a canal network. The former network includes a system of rail ferries across the Caspian Sea as an alternative to connect Kazakhstan to international ports.[15]
In case of the latter, all existing and projected canals cross through Russian territory. As such, those are briefly described in the appendix 7.7.

Considering the above, there is the following option for a rail-based transport chain:

- From the production site by rail to either the Port of Aktau or the Port of Kuryk on the Kazakhstan side of the Caspian Sea,
- rail wagons trajected by ferry to Azerbaijan (Port of Baku/Atal) and
- onwards to one of the two Georgian ports of Poti or Batumi at the Black Sea. Once cargo is at any port along the Black Sea Coast,
- there are all options to ship it by dedicated NH_3-tankers to international destinations in Europe, Americas and Asia using well-established technical and commercial solutions.

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[14] Production costs for NH3 in proximity to the export point in this assessment correspond to 827 USD/t(NH3) in the Small scale use case and 520 USD/t(NH3) in the Large scale use case
[15] Transports through Russia to the North or Iran to the South are not considered in this study.

4.3.3 Remarks for Shipping

If a rail-based transport chain along the transport route to Europe is to be excluded, pipelines and/ or maritime vessels can serve for the transport of H_2 or NH_3. To assess transport costs in the event of shipping across the Caspian Sea, it is assumed that “light” NH_3-vessels (reduced draft, i.e. “Caspian Sea sized”) will be available and used for ammonia shipping considering infrastructure and physical constrains of the respective waters (s. appendix 7.8).

Once cargo is at any port along the Black Sea Coast, there are all options to ship it to international destinations in Europe, Americas and Asia using well-established technical and commercial solutions.

4.3.4 Remarks for Pipelines

As already mentioned, pipeline-associated transport costs (LCOT) along the routes outside Kazakhstan will be estimated by

- approximated length/ distance of the respective route-sections, as well as
- using generic cost figures of the EHB initiative.

This approach differs from the more detailed assessment which was made for the transport cost calculation within the territory of Kazakhstan (s. section 4.2), which allows for distinguishing between the “Small Scale” and the “Large Scale” use-cases by considering, for example, different transport volumes and electricity prices. Cost estimates for LCOT of the EHB initiative are given only for the year 2040. To account for a cost decrease in the hydrogen economy after the ramp-up phase after all, a factor is used for applying a generic cost figure for the year 2030. Since the cost estimates of the pipeline assessment in Kazakhstan for the year 2040 and cost estimates in the EHB framework show comparable figures, it is decided that for the year 2030 similar cost estimates are reasonable to apply for the transport assessment outside of Kazakhstan (s.Table 10).

Table 10: Cost estimates for pipeline transport assessment

Reference	LCOT 2030 [USD/kgH_2/1000km]	LCOT 2040 [USD/kgH_2/1000km]	Remark
Domestic pipeline transport assessment Kazakhstan	0.96	0.23	s. section 4.2.2
EHB initiative	-	0.25*	Currency conversion factor USD-EUR 1.07
Assumption	1.03*		

* applied in pipeline transport assessment outside Kazakhstan

The derived LCOT in the assessment at hand do not consider potential additional cross-border-related expenses such as transit-tariffs, as this would be defined in future agreements and contracts which goes beyond a techno-economic assessment as undertaken in this study.

Approximated pipeline lengths are based on existing transmission pipelines for natural gas, as future H_2 pipelines are expected to be primarily based on existing infrastructure. An exception is the route section across the Caspian Sea, as to the date of writing, no gas pipeline is connecting the shores of Kazakhstan and Azerbaijan. In this case the length of a future pipeline is approximated by drawing a connection between the Kazakh coastline to the import point in Azerbaijan, i.e. Baku or Alat.

To account for technical requirements in the case of off-shore H_2 pipelines an additional factor is considered, based on the framework of the EHB. Compared to on-shore pipelines off-shore pipelines are anticipated to increase generic LCOT by appr. 50 % [85].

4.3.5 Route Section across the Caspian Sea

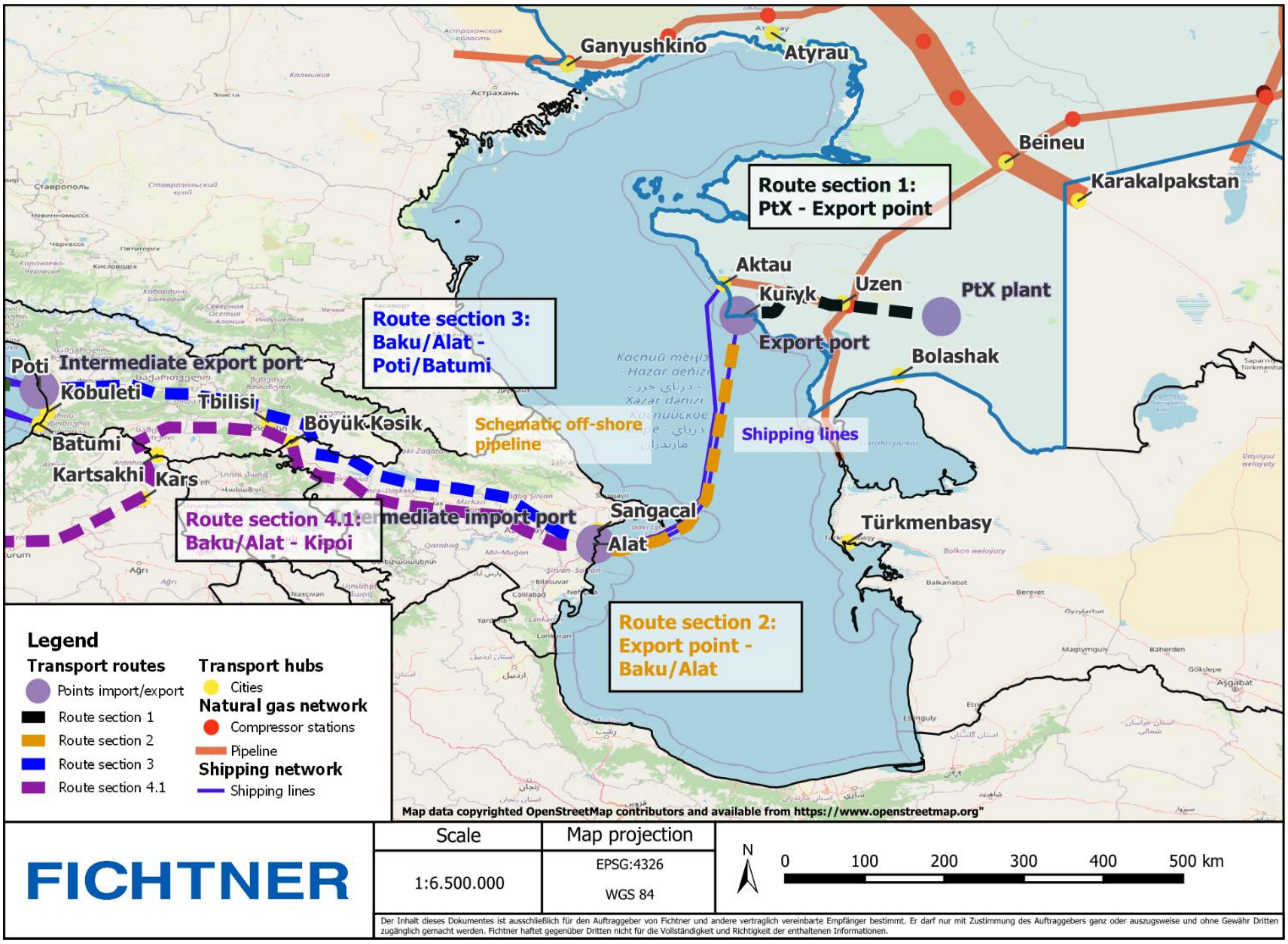

Figure 21: Route section across the Caspian Sea

From an economic point of view, the transport via rail wagons (crossing the Caspian Sea on dedicated ferries) and tank containers (crossing the Caspian Sea on dedicated container ships) are considered not feasible with regards to

- the volumes of NH_3 to be transported in the future (s. use-case definition in section 4.1) and
- the given infrastructure (marine and rail).

To accommodate the defined annual volumes of NH_3, respective tank-container, ferry and rail-wagon fleets would need to be increased substantially, as well as associated infrastructure in the form of rail and port terminals developed. An overview of the capacities needed for rail wagons, ferries and respective ship types is indicated in Table 11.

Table 11: Overview of rail and shipping alternatives across the Caspian Sea

Alternative	**Tank rail wagon on rail ferry**	**Tank container on container ship**	NH_3 **tanker**[16]
Capacitiy per rail wagon/ container unit/ LPG tanker [tNH_3]	56	16.6	7,000 (Caspian Sea sized) 15,000 (small) 41,000 (medium) >51,000 (large)[17]
Number of rail wagons container units needed "Small scale" 2030	17,858	60,241	n.a.
Number of rail wagons container units needed "Large scale" 2040	196,429	662,651	n.a.
Capacity of ferry for rail wagon/ container unit	54	125	n.a.
Number of journeys per year of ferries/ container ships needed "Small scale" 2030	331	482	143 (Caspian Sea sized) 66 (small) 25 (medium) 20 (large)
Number of journeys per year of ferries/ container ships/ LPG tankers needed "Large scale" 2040	3,638	5,302	1,572 (Caspian Sea sized) 717 (small) 269 (medium) 216 (large)

The assessment for maritime transport across the Caspian Sea will be made by considering dedicated NH_3 tankers.

[16] There are different ship sizes varying in draught, typically: 22,500 m³ capacity (small, draught 9 m), 60,000 m³ (medium, draught 11.5 m)), 75,000 m³ (large, draught 12.8 m). As described below and in the appendix 7.8, new NH3-tankers of unconventionally small transport capacities (in the magnitude of 7,000 t_{NH3}) would have to be provided for the Caspian Sea, accounting for limited draft in the Caspian Sea ports, as well as the challenge of building conventional NH3-tankers in shipyards on the Caspian Sea.
[17] Stated dimensions are indicative only. All tanker are designed to costumer needs and no completely clear industry standards exist.

Shipping via NH_3-tankers
Scenario: ammonia export in Kazakhstan

NH_3 can be loaded onto specialized NH_3-tankers, (comparable to LPG-transport), which ship NH_3 in (fully) refrigerated, thus liquid form. These vessels would most probably be employed under long-term charter agreements between the cargo owner (i.e. seller or buyer depending on off-take agreement) with the ship owner.

With regards to such vessels the feasibility of ship construction on the shores of the Caspian Sea without the cooperation of Russian shipyards can be challenging. To the best of the authors knowledge, no respective ship types (i.e. LPG-tankers, LH_2-tankers are not yet commercially available, also refer to section 7.5) operate in the Caspian Sea today. This can be of concern if there are limited water way connections to other international waters such as the Black Sea. If that is not the case, respective ship types could be delivered from shipyards in Japan or Korea. The Volga-Don-canal embodies the only promising water connection between the Black Sea and the Caspian Sea (s. section 7.7). However, the physical capacities of this connection (with regards to draft and beam) are limited and conventionally sized NH_3-vessels are not expected to enter the Caspian Sea via this water way, even at reduced load. A more feasible way of providing dedicated NH_3-tankers for marine NH_3-transport can be one of the options as follows:

- "Light" NH_3-tankers, specially designed to fit the Volga-Don-canal at reduced load but with max. transport capacities (i.e. Caspian Sea sized). Respective vessels could be delivered from any shipyard in the world with connection to international waters.
- Re-assembling NH_3-tankers at a shipyard in the Caspian Sea, after it has been shipped via the Volga-Don-canal in several parts to accommodate the physical limitations of the water way.

Appendix 7.8 further elaborates on the above-mentioned options, as well as briefly describe the potential option of retrofitting existing tankers (e.g. oil-tankers) to dedicated NH_3-tankers. Assuming one of those options finally allows to assess transport costs of NH_3-shipping across the Caspian Sea.

Table 12 shows associated landed costs of NH_3 at the end of the transport route at the Caspian Sea port of Baku/ Alat.

Table 12: Landed costs of ammonia after shipping ammonia across the Caspian Sea

Starting-point of route section	**End-point of route section**	**Distance**	**Landed costs of NH_3 at end-point "Small scale" [USD/tNH_3]**	**Landed costs of H_2 at end-point "Large scale" [USD/t NH_3]**
Kazakh coast	Baku/ Alat	Appr. 500 km	885.0	559.3

Pipelines
Scenario: hydrogen export in Kazakhstan

An alternative transport option to cross the Caspian Sea is the construction of an off-shore pipeline. Theoretically speaking, the construction of an NH_3 pipeline embodies an option, if the final product produced in Kazakhstan will be green NH_3 (*Scenario: Ammonia export in Kazakhstan*). However, to the best of the authors knowledge the few examples of long-distance NH_3 pipeline transport in the U.S., Russia and Ukraine, as well as Europe are exclusively on-shore. Considering the hazardous nature of NH_3 the feasibility of an off-shore NH_3 pipeline across the Caspian Sea under aspects of safety and environmental risks is questionable, which is why the alternative of an off-shore NH_3 pipeline will not be further explored in this study.

On the other hand, the option of an off-shore H_2 pipeline is more feasible. There are numerous examples of off-shore transmission pipelines for natural gas in the world, and the fact that existing natural gas pipelines can be repurposed for dedicated H_2 transport supports the idea of off-shore H_2 transmission. Also several project plans for new H_2 off-shore transmission pipelines were already published [59], [60].

The availability of dedicated ships needed for the laying of off-shore pipelines in the Caspian Sea has already been demonstrated, since several pipelines for natural gas are already installed and in operation to deliver gas from off-shore oil and gas fields to the shores of Kazakhstan, Azerbaijan and Turkmenistan.

A relevant aspect when considering off-shore pipelines across the Caspian Sea is the fact that the Caspian Sea basin encouters earth quakes from time to time [82] [83] [84] which can affect the operational life time and performance of a pipeline. As there are other pipelines connected to oil and gas production sites already in place, the risk of potential earth quakes at this stage should not be regarded as a "show-stopper" for future planning. However, it is advised to consider this aspect in further studies at a later project stage.

Assuming a distance of 500 km and using the cost figure for off-shore pipelines of 0.32 EUR/kgH₂/1,000km results in associated levelized transport costs for route-section 2 of 0.78 USD/kgH₂ in 2030 and 0.19 USD/kgH₂ in 2040.[18] Added to the assumed costs of production with pipeline-associated transport[19] from production site to export point at the coast of Kazakhstan figures for the landed costs of H_2 in Baku/ Atal can be derived for the use-cases "Small scale" 2030 and "Large scale" 2040. The respective figures are given in

Table 13.

Table 13: Off-shore hydrogen pipeline across Caspian Sea

Starting-point of route section	End-point of route section	Distance	Landed costs of H_2 at end-point "Small scale" [USD/kgH_2]	Landed costs of H_2 at end-point "Large scale" [USD/kgH_2]
Kazakh coast	Baku/ Alat	Appr. 500 km	4.88	2.64

[18] currency conversion factor USD/EUR assumed 1.07.
[19] cost figure taken for a 1,000 km distance (refer to section 4.2.2)

4.3.6 Route Section between Caspian Sea and Black Sea

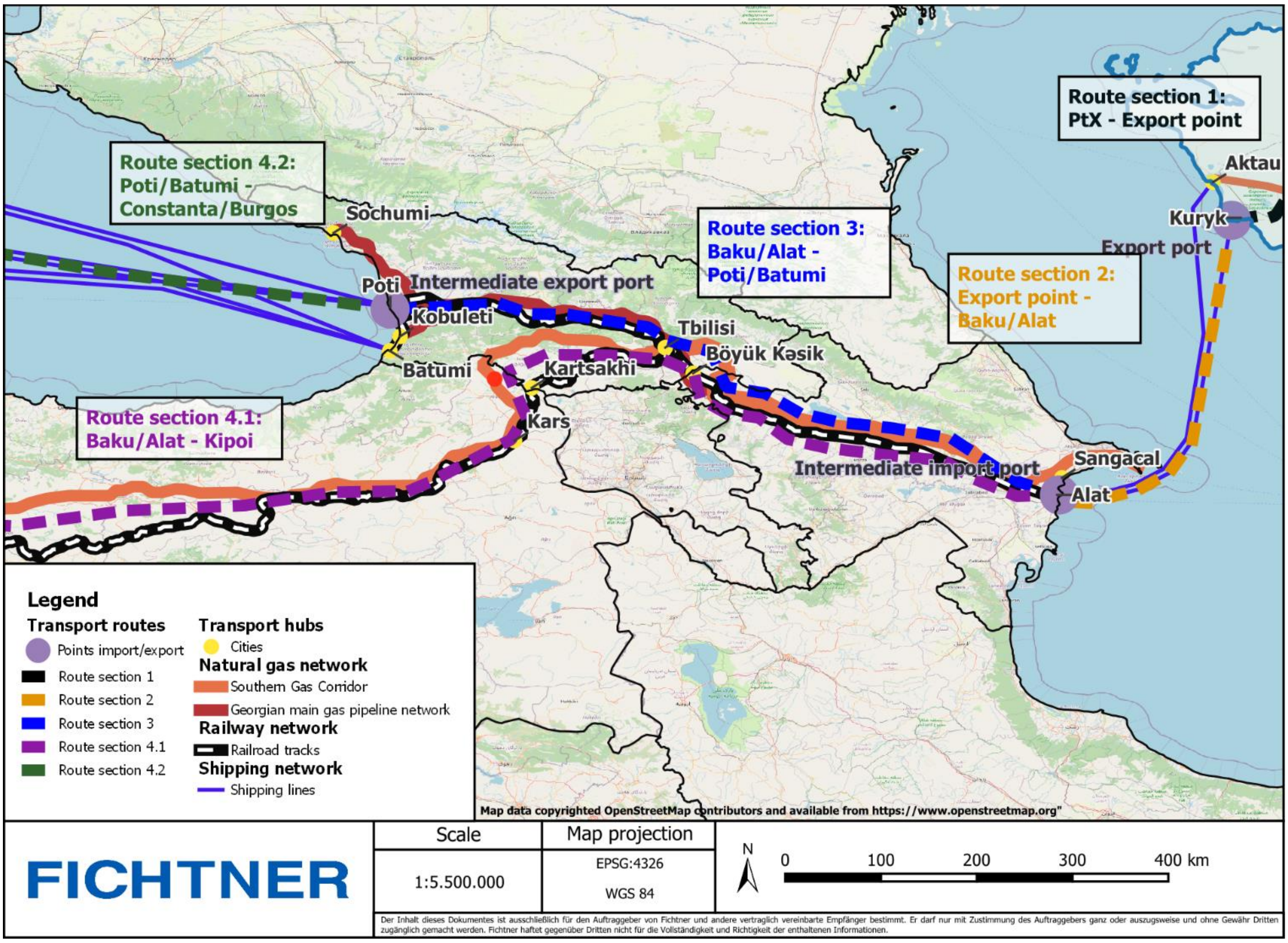

Figure 22: Route section between Caspian Sea and Black Sea

Rail

Scenario: ammonia export in Kazakhstan

In case the needed expansion of port terminals and related vessel capacities can be achieved, transport planning needs to consider existing rail corridor capacities in Kazakhstan, Azerbaijan and Georgia. To move 18,000 rail wagons or similar number of tank containers in the Small scale use-case appr. 780 train pairs (back and forth) per year are estimated (@ 400 m usable train length equaling up to 24 wagons/train) or appr. 440 pairs if 700 m usable train length can be used (equaling up to 41 wagons/train). In the best case of 440 trains per year, this would mean 1.2 trains on average per day along this corridor which would need a high degree of scheduling reliability from the network as well as from the rail operators´ sides.

Desk-based, this is difficult to assess whether this would be achievable. However, central European experience of cross-border rail freight suggests that this requires some management attention as well as available train slots on already highly congested and run-down networks along the transport route.

In case capacities could still be sufficiently addressed, at the Western side of the corridor - i.e. at the Black Sea - rail transport would end up in either in the Ports of Poti or Batumi, or alternatively in ports in Türkiye (s. section 4.3.8).

The Georgian ports of Poti and Batumi provide cargo handling facilities for oil and oil products, dry bulks, general cargoes as well as containers. Poti positions itself as an important Central Asia-Europe intermodal hub stressing the first call of CMA CGM's new Caucasus Georgia Express (CGX) service [72]. Playing a key role in this new intermodal service, APM Terminal at Poti works as a hub for cargo consolidation and dispatch, connecting trains directly from the Middle Corridor to Georgia, for onward maritime transport to and from Greece and Türkiye.

Batumi is the main container, ferry and general cargo seaport in Georgia [73]. A wide range of oil, crude oil and oil products are handled, in total c. 12.2 Mtpa of cargo, and c. 100,000 TEU p.a. [74]. Bulk cargo includes grain, green sugar, scrap metal and ore; general cargo includes steel pipes and wood products. Rll-on-Roll-off (RoRo), railway ferry facilities and a container terminal are also available. The Port of Batumi serves as an alternative to the Port of Poti but is apparently less well served by the Georgian railways.

Nevertheless, in any port, buffering incoming train loads and outgoing larger vessel loads requires NH_3 storage. As all ports in the area feature port areas enclosed by urban sprawl, this raises questions of space availability and of safety. Especially the latter is regarded in utmost concern, as the explosion in the Lebanese port of Beirut some time ago impressively showed.

Above´s storage challenges provide a case for a pipeline running from Kazakhstan to the Black Sea hitting the coast on a greenfield site (refer to section 4.3.5). Downstream storage could be provided in a floating unit, thus avoiding existing ports in terms of urban areas (safety, plot availability) and depth restrictions.

Pipelines

Scenario: ammonia export in Kazakhstan

As already pointed out in section 4.3.5 ammonia pipelines do exist for long-distance transport. Examples can be found in the United States, Russia and Ukraine. Ammonia pipeline transport would require both pumping stations and pipelines (refer to appendix 7.1). In the event of ammonia unloading in the port of Alat, Azerbaijan (after shipment across the Caspian Sea via dedicated NH_3-tankers), NH_3 can potentially be delivered to a Black Sea port in Georgia via a new and dedicated NH_3 pipeline on-shore along route section 3.

Despite the fact, that a NH_3 ammonia pipeline assessment is not included in this study, Fichtner can provide indicative figures on LCOT for NH_3 pipeline transport derived from previous studies with a similar use-case analysis.

In this way, the transport option of further ship-loading H_2 in the form of NH_3 at a designated Black Sea port in Georgia and final delivery to a European port can be further assessed and compared the hydrogen export scenario.

Assuming a distance of 800 km and approximating the cost figures from similar studies results in associated levelized transport costs for route-section 3 of 121.0 USD/tNH_3. in 2030 and 30.7 USD/tNH_3 in 2040. Added to the Landed costs of ammonia (LCOA) at the end point of route-section 2 (i.e. Baku/ Alat) figures for the LCOA in Poti/ Batumi can be derived for the use-cases “Small scale” 2030 and “Large scale” 2040. The respective figures are given in Table 14.

Table 14: On-shore ammonia pipeline through Azerbaijan and Georgia

Starting-point of route section	**End-point of route section**	**Distance**	**Landed costs of** NH_3 **at end-point “Small scale” [USD/t**NH_3**]**	**Landed costs of** NH_3 **at end-point “Large scale” [USD/t**NH_3**]**
Baku/ Alat	Poti/ Batumi	Appr. 800 km	1,006.2	590.0

Pipelines
Scenario: hydrogen export in Kazakhstan

A natural gas pipeline corridor for H_2 transmission between the Caspian Sea and the Black Sea would cross Azerbaijan and Georgia. The potential pipeline infrastructure for this is provided by the "South Caucasus Pipeline" (SCP) and the main natural gas pipeline system in Georgia. The SCP is part of the "Southern Gas Corridor" (SGC). The SGC is currently used for the transmission of natural gas from Azerbaijan via Georgia and Türkiye to the endpoint in Italy and represents a good basis for a future H_2 transport corridor due to the merger of the pipeline sections in the participating countries. There are also indications based on statements from politicians for the potential use of the SGC as H_2 pipeline or for H_2 blending.

During the "9th Southern Gas Corridor Advisory Council Ministerial Meeting" and the "1st Green Energy Advisory Council Ministerial Meeting" in Baku in early 2023, the president of the Republic of Azerbaijan Ilham Aliyev spoke of good cooperation and exchange with the European Union (EU) in terms of H_2 and expressed confidence in the implementation of renewable energy projects in the future. At the same event, Parviz Shahbazov, Azerbaijan's Minister of Energy, spoke of an expansion of the cooperation into green spheres due to the president's strategic vision. In addition, EU commissioner for energy Kadri Simson mentioned a long-term and sustainable energy partnership between the EU and Azerbaijan that focuses on renewable energy and the importance of the SGC. [67, 58] In Georgia the German government supports financially the country's first green H_2 production project which therefore positively effects the speed of the energy and infrastructure transition and is beneficial for future cooperation [68]. Furthermore, the "Trans Adriatic Pipeline" (TAP) that is part of the SGC and which is the section from Türkiye border to Italy is currently getting H_2 ready [57, 58]. However, so far there is no decided plan regarding the use of the SGC for H_2 transport.

The potential pipeline route starts at the port of Sangachal in Azerbaijan, located in between Baku and Alat (Figure 22). From here, the SCP runs northwest until it crosses the border with Georgia north of Aghstafa and passes Tiblisi to the Turkish border at Vale. The total length of the pipeline amounts 692 km with a diameter of 1,066 mm. The pipeline was expanded for a length of 489 km by a second tube with a diameter of 1,200 mm. The capacity of the pipeline totals 24 bcm natural gas per year. Via the Georgian main gas pipeline network, Poti, Sochumi and Kobuleti at the Black Sea can be reached by gas transports. Diameters of the pipeline sections vary between 500 mm and 800 mm. [69, 70]

Assuming a distance of 800 km and using the respective cost figures (s. section 4.3.4) results in associated levelized transport costs for route-section 3 of 82 USD/kgH_2 in 2030 of 0.20 USD/kgH_2 in 2040. Added to the LCOH at the end point of route-section 2 (i.e. Baku/ Alat) figures for the landed costs of H_2 in Poti/ Batumi can be derived for the use-cases "Small scale" 2030 and "Large scale" 2040. The respective figures are given in Table 15.

Table 15: On-shore hydrogen pipeline through Azerbaijan and Georgia

Starting-point of route section	**End-point of route section**	**Distance**	**Landed costs of H_2 at end-point "Small scale" [USD/kgH_2]**	**Landed costs of H_2 at end-point "Large scale" [USD/kgH_2]**
Baku/ Alat	Poti/ Batumi	Appr. 800 km	5.71	2.83

4.3.7 Route Section across the Black Sea

In the hydrogen export scenario H_2 has been delivered to potential Black Sea ports in Georgia, i.e. Poti or Batumi. There, the H_2 can be converted to NH_3 and loaded onto respective vessels which would have access via ocean roads to any major import port in the world. The feasibility of new NH_3 production plants, as well as new export terminals at the port site is not included in this study. The following scenario (route section 4.2) serves to compare an alternative to hydrogen pipeline delivery from Kazakhstan to South-East-Europe, crossing the country of Türkiye (route section 4.1).

Alternatively, ships could also be loaded with liquefied H_2 (LH_2) instead of NH_3. In this case the process of NH_3 synthesis is replaced by the liquefication process of H_2 that would take place at the respective Black Sea export port.

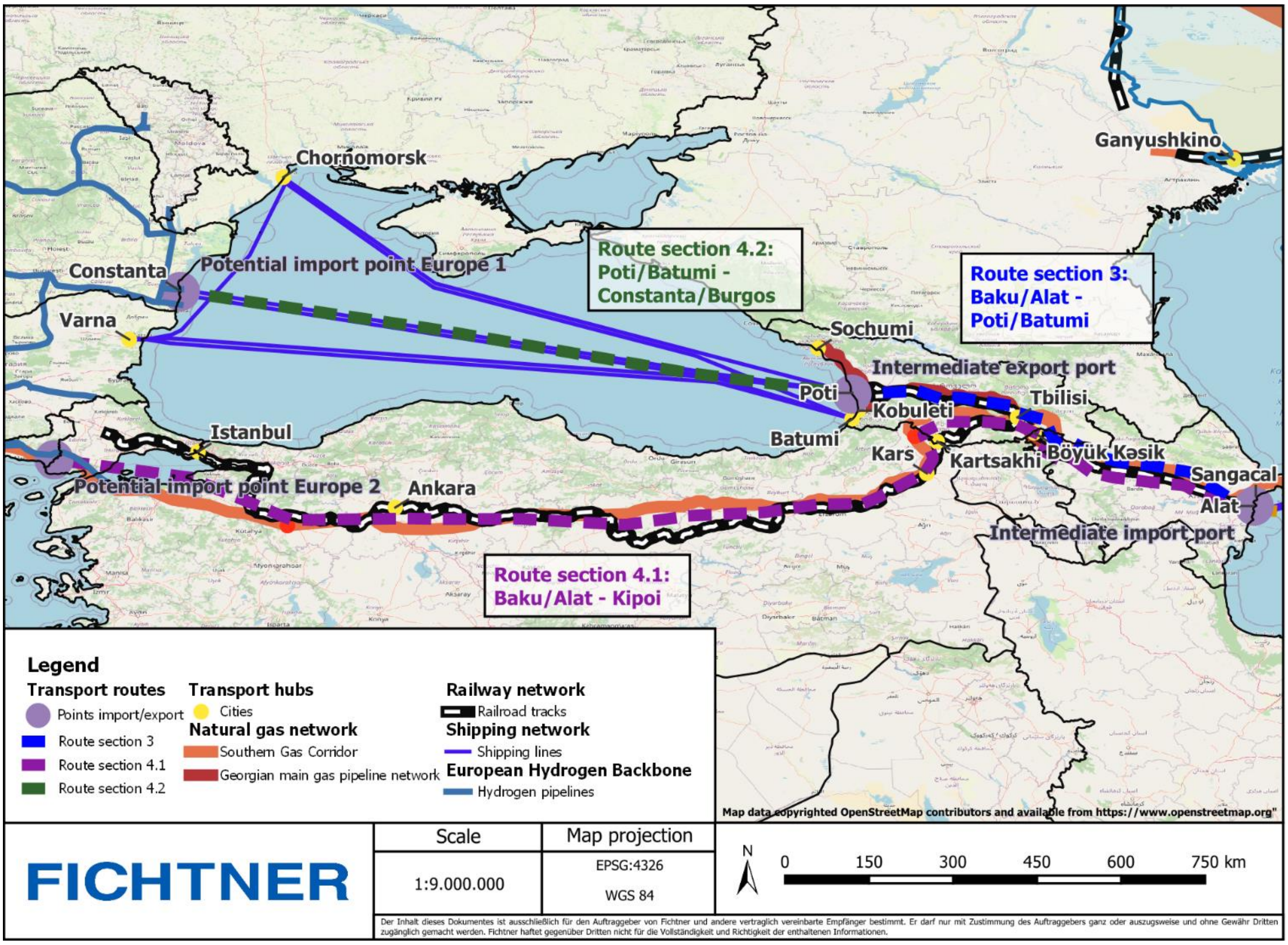

Figure 23: Route section across the Black Sea

Shipping

Scenario: hydrogen export in Kazakhstan

Once the NH_3 is being available in a Black Sea port, it can be loaded onto specialized NH_3-tankers, (comparable to LPG-transport), which ship NH_3 in (fully) refrigerated, thus liquid form (also refer to appendix 7.4). These vessels would most probably be employed under long-term charter agreements between the cargo owner (i.e. seller or buyer depending on off-take agreement) with the ship owner.

Typical size-types of conventional NH_3 tankers range from 22,500 m^3 (or even smaller) up to 84,000 m^3 carrying capacity. Almost 95% of the global NH_3 tanker fleet can be allocated to this size-type range. A 22,500 m^3-vessel typically draws 9.0 m, a 60,000 m^3-vessel 11.5 m and a 75,000 m^3-vessel 12.8 m.

In case the question of sufficient and safe port storage capacity (and resulting safety concerns) can be addressed, the Ports of Poti and Batumi currently can take vessel up to a draft of 9 m only (12.2 m in case of tankers in Port of Poti), which excludes using larger NH_3-tankers, thus limiting the possibility to realize economies of scale for international maritime transport based on today's available infrastructure [75, 76].

Table 16 shows associated landed costs of H_2 at the end of the transport route at the European Black Sea ports of Constanta or Burgas. To emphasize the flexibility of shipping an alternative European port of destination, i.e. Rotterdam was also analysed. Figure 24 shows the split of costs for shipping NH_3 across the Black Sea for the "Small scale" use-case.

Table 16: Landed costs of hydrogen after shipping ammonia across the Black Sea

Starting-point of route section	**End-point of route section**	**Distance**	**Landed costs of H_2 at end-point "Small scale" [USD/kgH_2]**	**Landed costs of H_2 at end-point "Large scale" [USD/kgH_2]**
Poti / Batumi	Constanta/ Burgas	~1,100 km	9.21	4.92
Poti / Batumi	Rotterdam	~6,900 km	9.62	5.29

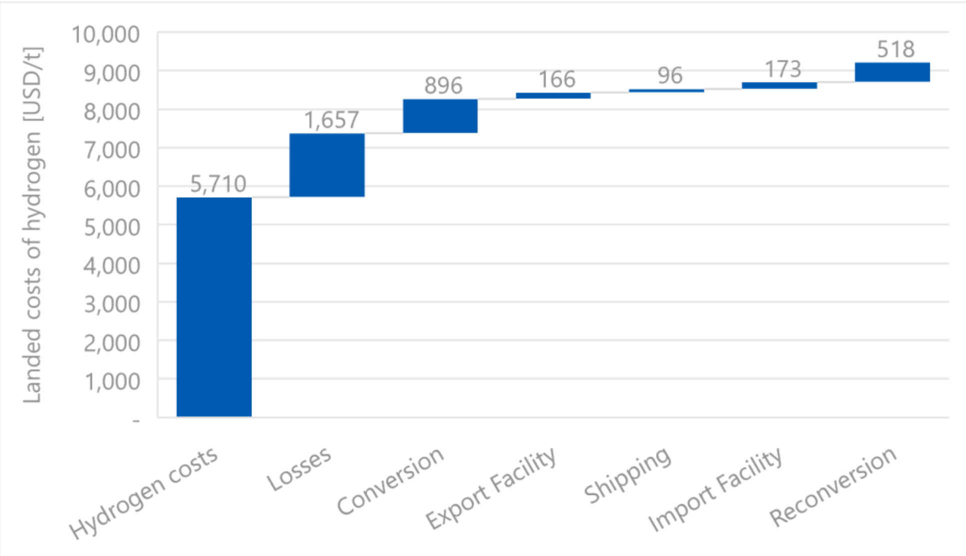

Figure 24: Cost split example: Landed costs of hydrogen via ammonia transport value chain for a transport from Poti/Batumi to Constanta/Burgas in 2030

Ship (Liquefied hydrogen)

Scenario: hydrogen export in Kazakhstan

Today shipping of liquefied hydrogen (LH_2) does not exist on a commercial scale. Kawasaki has a pilot project running with a capacity of 89 tons of hydrogen.

Although the largest vessel manufacturer in the world (Kawasaki Heavy Industries, Samsung Heavy Industries, KSOE) are very interested in the production of the vessel the development of a commercial product is still challenging. The extremely low temperatures (even for cryogenic systems) are leading to challenging design problems for the storages as well as the safety equipment.

The aim of the vessel manufacturers is to develop multiple sizes of LH_2 carriers, starting with commercial vessels with a capacity of e.g. 20,000 m³ / ~ 1,600 t. On the medium to long-term future common LPG and LNG carrier sizes of 80,000 and 160,000 m³ / 6,320 t and 11,230 t per vessel are the expected vessel sizes also for LH_2 vessels.

Table 17 shows associated landed costs of H_2 at the end of the transport route at the European Black Sea ports of Constanta or Burgas. To emphasize the flexibility of shipping an alternative European port of destination, i.e. Rotterdam was also analysed. Figure 25 shows the split of costs for shipping LH_2 across the Black Sea for the "Small scale" use-case.

Table 17: Landed costs of hydrogen after shipping liquified hydrogen across the Black Sea

Starting-point of route section	End-point of route section	Distance	Landed costs of H_2 at end-point "Small scale" [USD/kgH_2]	Landed costs of H_2 at end-point "Large scale" [USD/kgH_2]
Poti/ Batumi	Constanta/ Burgas	~1,100 km	10.07	4.47
Poti / Batumi	Rotterdam	~6,900 km	11.35	5.12

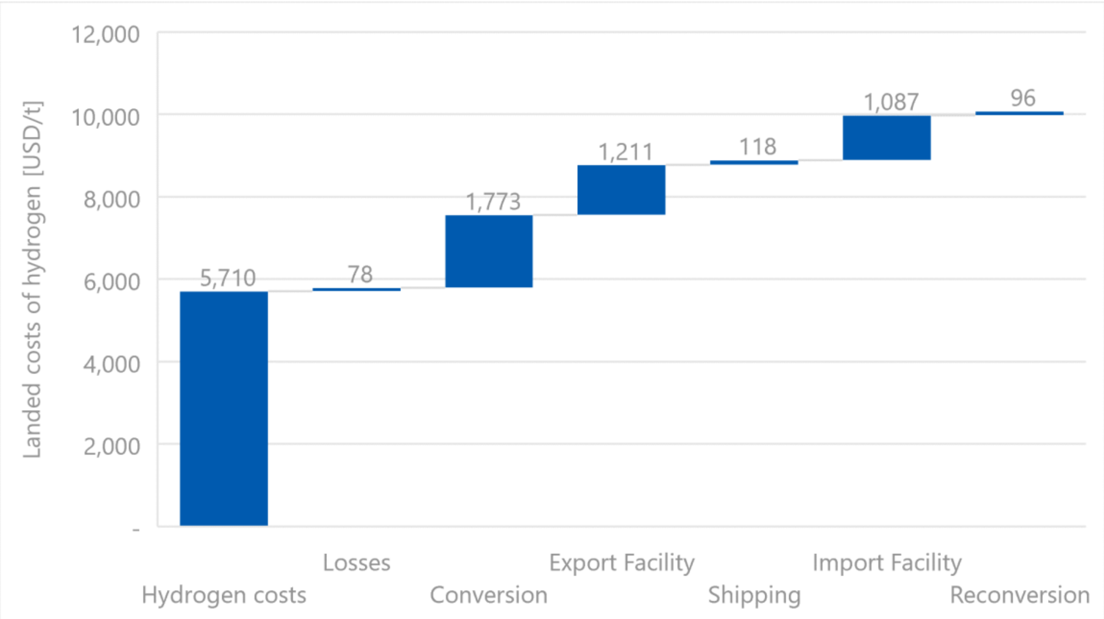

Figure 25: Cost split example: Landed costs of hydrogen via liquified hydrogen transport value chain for a transport from Poti/Batumi to Constanta/Burgas in 2030

Assumptions made for shipping assessment:

All assumptions used for the cost assessment via shipping are shown in Section 7.10. It must be noted that quite a substantial amount of parameters are project related (e.g. electricity prices in both ports) and that both NH_3 cracking and large scale LH_2 are today not yet commercially available, which means the predicted transport costs are only a cost assessment based on today's available information.

4.3.8 Route Section across Türkiye

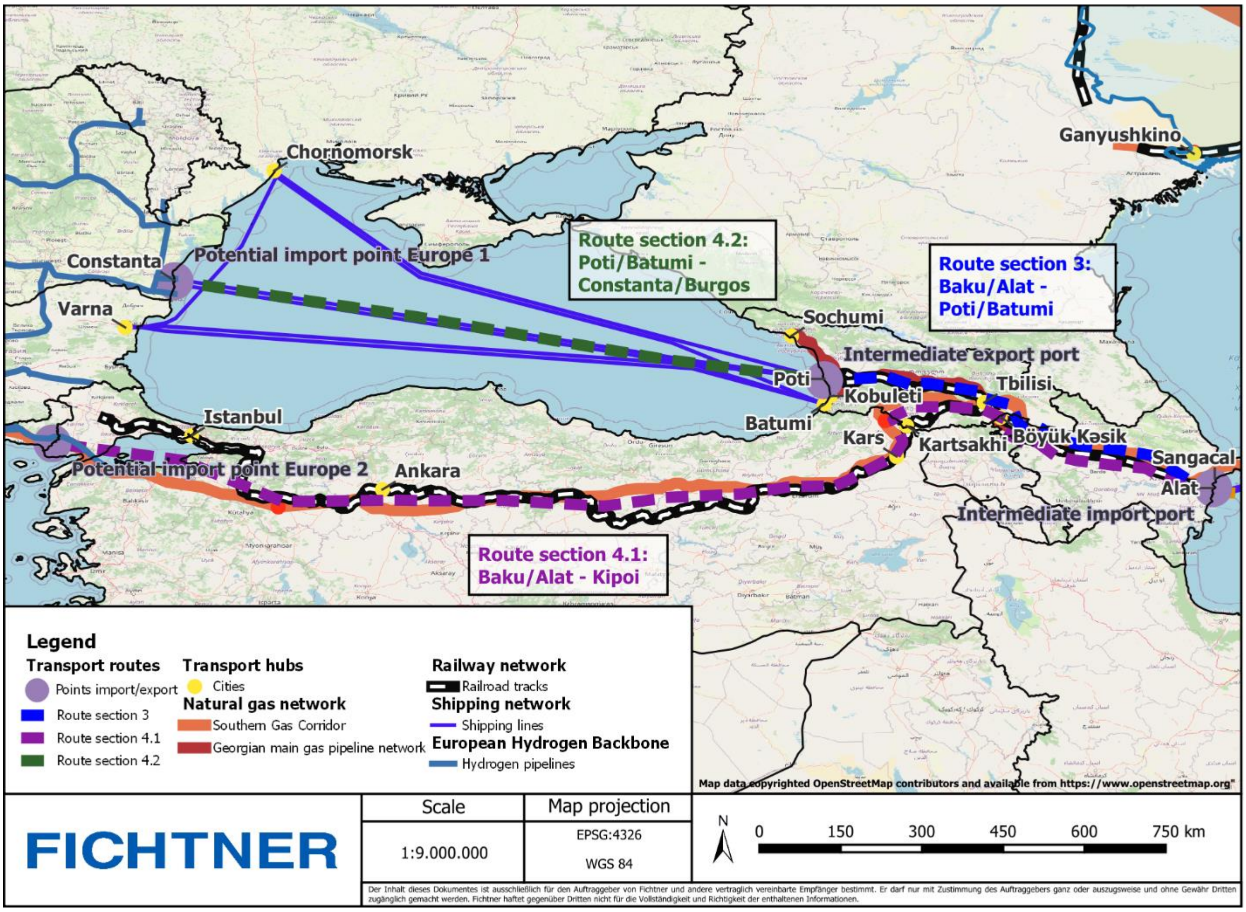

Figure 26: Route section across Türkiye

Rail

Scenario: ammonia export in Kazakhstan

As stated in section 4.3.6 rail transport between the Caspian and the Black Sea would end up in either in the Ports of Poti or Batumi, or alternatively in ports in Türkiye. We deem a Western end of the rail corridor in Türkiye as unrealistic, as this would need to change the rail gauge from the Russian 1,520 mm wide gauge to the central European (including Türkiye) normal gauge of 1,435 mm. Hence, going to either Poti or Batumi seems to be the more efficient option.

However, once an efficient gauge change can be affected, there is only one possibility to run direct trains from the Turkish network below the Bosporus at Istanbul to reach European territory - via the Marmaray tunnel. According to press clippings, this tunnel has seen a successful train run from China to the Czech capital of Prague via Baku. [77] It is a novelty in the sense that it runs uninterrupted from Baku to Europe, thanks to its passage though the Marmaray Tunnel. This tunnel was previously only open to passenger trains. However, this tunnel does not allow freight trains carrying hazardous goods in bulk on a regular basis. Hence, going to either Poti or Batumi (as final train destination) remains the only alternative if rail-transport shall be used along the Middle-Corridor.

Pipeline

Scenario: hydrogen export in Kazakhstan

The potential of the implementation of green H_2 in the future Turkish energy system is described in a strategy paper and roadmap by the "Republic of Türkiye Ministry of Energy and natural Resources" which were published in early 2023 [55]. Türkiye aims for a net zero carbon emission energy system by 2053. A priority field for reaching this target is green H_2. The plan includes the development of a H_2 economy in Türkiye covering the entire value chain from the production to storage, transportation and usage.[20]

Türkiye sees a new export potential in green H_2 and intends to establish itself as an exporter as well as due to its strategically important location as a transit country for H_2 between Asia and Europe. Therefore, a part of the defined strategy is the development of collaborations with countries involved in a global H_2 market in terms of H_2 transmission and marketing. Part of the transportation network will be pipelines. A H_2 pipeline network will be created by 2053 and includes the conversion of existing natural gas pipelines for H_2 transmission and blending. The suitability of the existing pipelines is to be assessed for this purpose according to [55].

A possible pipeline route for the H_2 transmission to Europe is the "Trans-Anatolian Natural Gas Pipeline" (TANAP) which is a part of the previously described SGC. [58]

The TANAP starts at the Georgian border connected to the South Caucasus Pipeline at Vale and runs 1,793 km west through Türkiye to Greece. The pipeline varies in diameter between 1,200 mm and 1,422 mm. At the Dardanelles the pipeline crosses the sea. Therefore, a dual subsea pipeline with a diameter of 900 mm each is installed. At Kipoi the TANAP ends and connects with the Trans Adriatic Pipeline in Greece. The TANAP is in total 1,793 km long and its capacity reaches 16.2 bcm natural gas per year. [71]

Assuming a distance of 2,300 km and using the cost figure of 0.23 EUR/kgH_2/1,000km results in associated levelized transport costs for route-section 4.1 of 2.36 USD/kgH_2 in 2040 and 0.57 USD/kgH_2 in 2040. Added to the LCOH at the end point of route-section 2 (i.e. Baku/ Alat) figures for the landed costs of H_2 in Kipoi can be derived for the use-cases "Small scale" 2030 and "Large scale" 2040. The respective figures are given in Table 18.

Table 18: On-shore hydrogen pipeline across Azerbaijan, Georgia and Türkiye

Starting-point of route section	End-point of route section	Distance	Landed costs of H_2 at end-point "Small scale" [USD/kgH_2]	Landed costs of H_2 at end-point "Large scale" [USD/kgH_2]
Baku/ Alat	Kipoi	Appr. 2,300 km	7.25	3.20

[20] Due to a good potential for low-cost energy from renewable energy sources, it is planned to reduce the green H2 production costs to 2.4 USD/kg$_{H2}$ and less by 2035 and below 1.2 USD/kg$_{H2}$ by 2053. Electrolysis capacities are targeted to be gradually increased to 2 GW by 2030, 5 GW by 2035 and 70 GW by 2053.

4.3.9 Results Overview and Remarks

An overview of the respective route-sections and associated LCOT as well as landed costs of hydrogen (LCOH) at the end of the route is given in Table 19 and Figure 28.

Table 19: Findings overview for landed costs of hydrogen (Scenario: hydrogen export in Kazakhstan)

Route section	Starting point	End point	Length/ Distance [km]	Transport option	LCOT for route section [USD/kgH_2]	LCOH at end point (Small scale) [USD/kgH_2]	LCOH at end point (Large scale) [USD/kgH_2]
1	PtX plant *Kazakh territory, e.g. Mangistau region*	Export point *Kazakh coastline*	1,000	H_2 pipeline	0.96 (Small scale) 0.23 (Large scale)	4.10	2.45
2	Export point *Kazakh coastline*	Interm. import port *Baku or Alat*	500	H_2 pipeline	0.78 (Small scale) 0.19 (Large scale)	4.88	2.64
3	Interm. import port *Baku or Alat*	Interm. export port *Poti or Batumi*	800	H_2 pipeline	0.82 (Small scale) 0.20 (Large scale)	5.71	2.83
4.1	Inerm. import port *Baku or Alat*	Pot. import point Europe 2 *Kipoi*	2,300	H_2 pipeline	2.36 (Small scale) 0.57 (Large scale)	7.25	3.20
4.2	Interm. export point *Poti or Batumi*	Pot. import point Europe 1 *Constanta or Burgas*	1,100	NH_3 shipping	3.50 (Small scale) 2.09 (Large scale)	9.21	4.92
4.2	Interm. export point *Poti or Batumi*	Pot. import point Europe 1 *Constanta or Burgas*	1,100	LH_2 shipping	4.36 (Small scale) 1.64 (Large scale)	10.07	4.47

As an alternative to transporting the medium H_2, the transport of NH_3 via the Black Sea has been assessed. A breakdown of LCOH as in Table 19 for each route section is not applicable since the product at the intermediate end points is NH_3 and not H_2. Hence, LCOH are given only at the European import ports, after reconverting NH_3 to H_2. An overview of the respective route-sections is given in Table 20.

Table 20: Findings overview of landed costs of ammonia (Scenario: ammonia export in Kazakhstan)

Route section	Starting point	End point	Length/ Distance [km]	Transport option	LCOT for route section [USD/tNH_3]	LCOA at end point (Small scale) [USD/tNH_3]	LCOA at end point (Large scale) [USD/tNH_3]
2	Export point (i.e. NH_3 production site) *Kazakh coastline*	Interm. import port *Baku or Alat*	500	NH_3 shipping	58.0 (Small scale) 39.3 (Large scale)	885.0	559.3
3	Interm. import port *Baku or Alat*	Interm. export port *Poti or Batumi*	800	NH_3 pipeline	121.2 (Small scale) 30.7 (Large scale)	1,006.2	590.0
4.2	Interm. export point *Poti or Batumi*	Pot. import point Europe 1 *Constanta or Burgas*	1,100	NH_3 shipping	60.7 (Small scale) 41.0 (Large scale)	1066.9	631.0

When converted to H_2 at the European port of destination (PoD), LCOH at the end point of route section 4.2 can be compared to the scenario described in Table 19. Associated LCOH considering ammonia transport from Kazakhstan to Europe are as follows:

Table 21: Landed costs of hydrogen after re-conversion at the port of destination considering export alternative of ammonia transport (Scenario: ammonia export in Kazakhstan)

Starting point	End point (PoD)	LCOH at PoD (Small scale) [USD/kgH_2]	LCOH at PoD(Large scale) [USD/kgH_2]
Export point (i.e. NH_3 production site) *Kazakh coastline*	Pot. import point Europe 1 *Constanta or Burgas*	8.31	4.79
Export point (i.e. NH_3 production site) *Kazakh coastline*	Rotterdam	8.71	5.16

Fehler! Verweisquelle konnte nicht gefunden werden. shows transport-related cost shares of different transport routes and options. In the case of shipping-related transport costs, landed costs of hydrogen up to the point of H_2 conversion (to either NH_3 or LH_2) and loading must also be taken into account in order to price inefficiencies along the transport value chain, e.g. due to boil-off losses. This also implies costs for the initial production of H_2. For the transport assessment at hand, production costs have been assumed in accordance with the use-case definition (s. section **Fehler! Verweisquelle konnte nicht gefunden werden.**). It must be pointed out, that when other production costs were assumed, shipping-related transport cost figures will change accordingly.

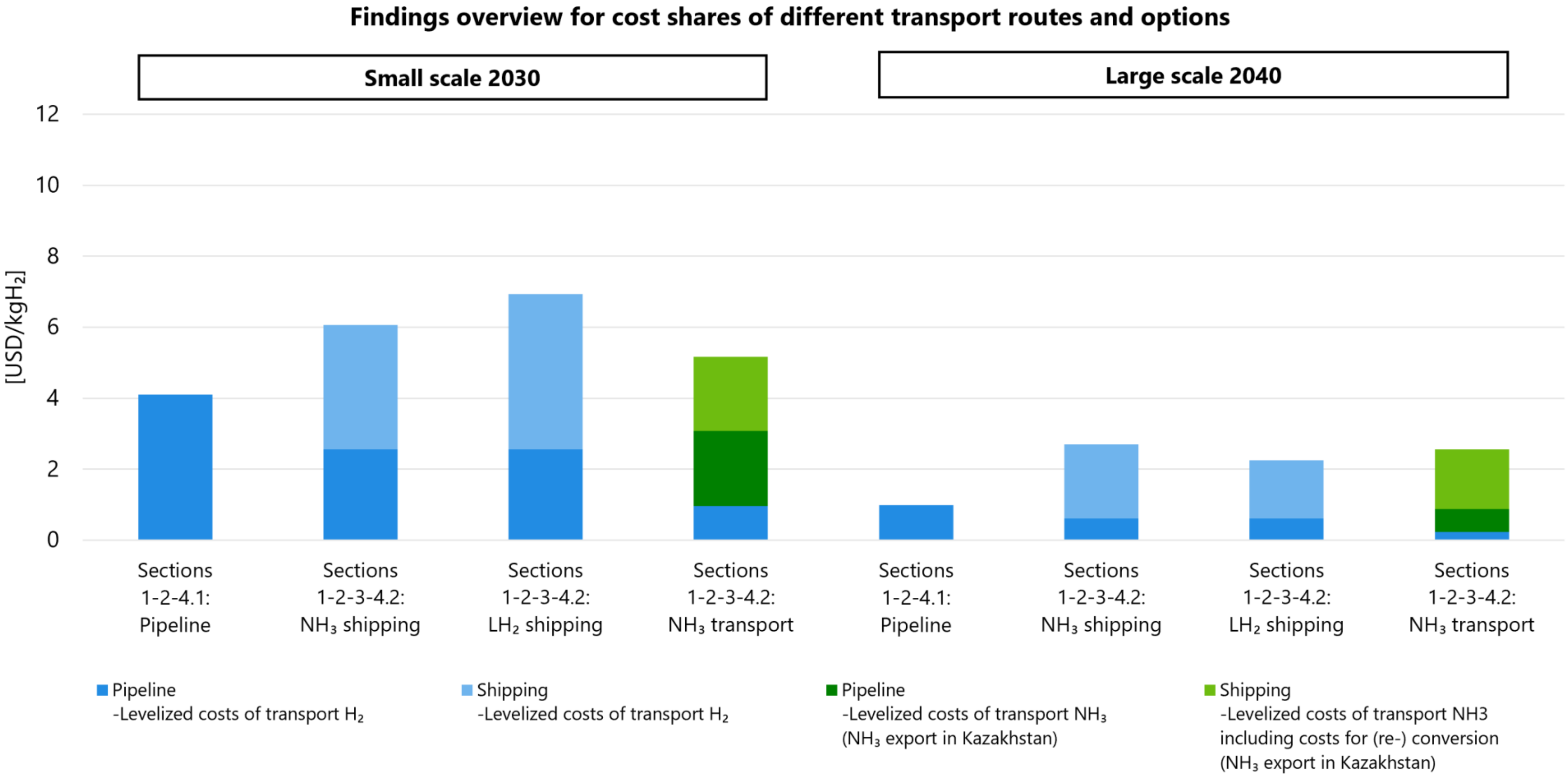

Figure 27: Findings overview for cost shares of different transport routes and options

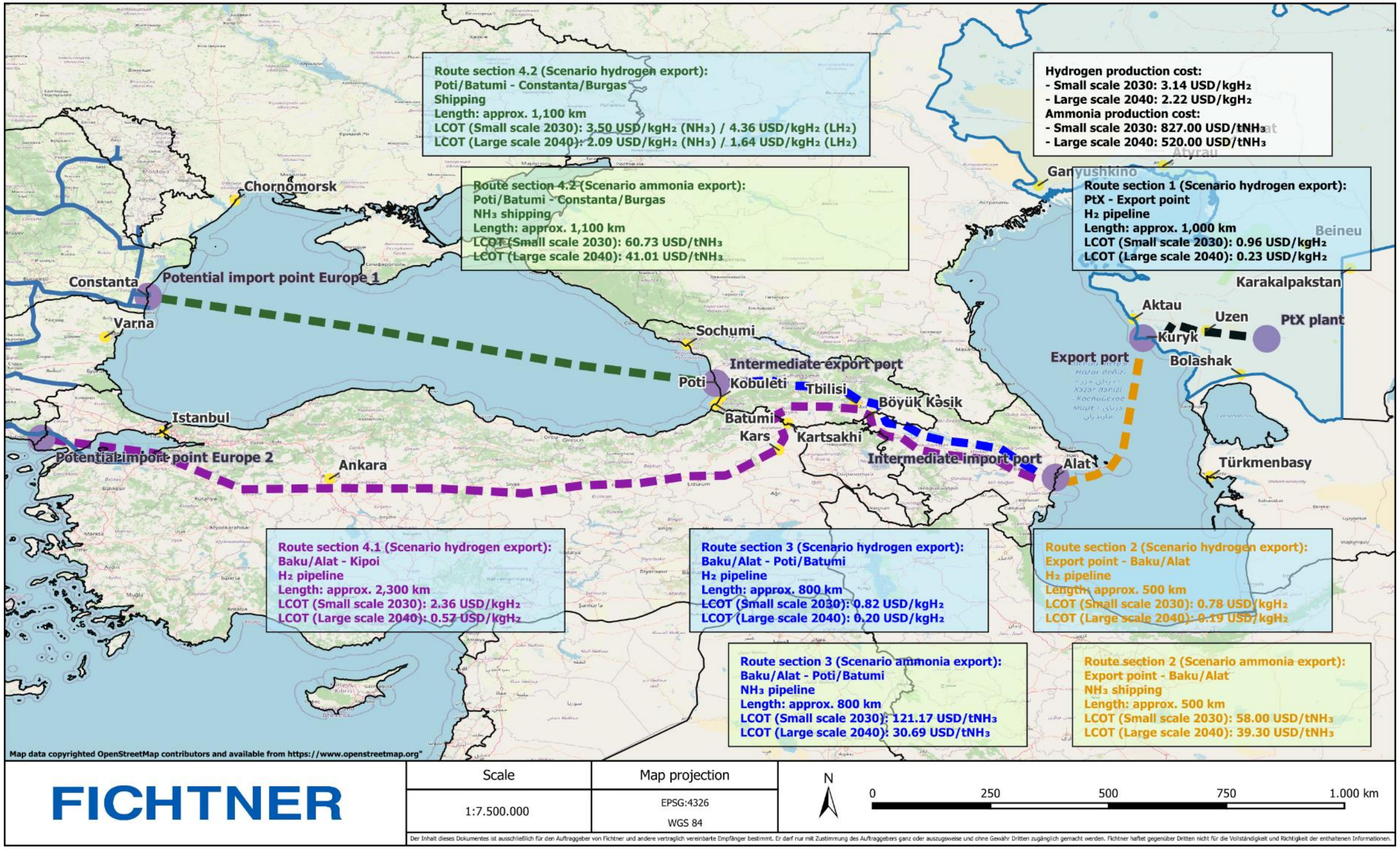

Figure 28: Results overview of route sections between Kazakhstan and South-East-Europe

Concluding remarks on the hydrogen transport assessment

For each route section along the so-called Middle Corridor between Kazakhstan and South-East-Europe, several transport options from a techno-economic point of view have been discussed in the light of pre-defined use-cases and associated indicative cost estimates for the transport-related costs of H_2 have been assessed. As already explained in section 3.3, the assessment of future costs - in this case levelized costs of transport (LCOT) as well as LCOH - is subject to uncertainties in the respective target years 2030 and 2040 which is why the provided cost figures must be regarded with caution. Nevertheless the assessment considered the feasibility of various transport options for future H_2 export from Kazakhstan to South-East-Europe, based on technological, infrastructural and economic challenges that will be encountered if the defined use-cases are drawn to the discussion.

With regards to trans-border pipeline transport uncertainties remain which cannot be further assessed in this study. This primarily concerns the availability and capacities of future pipeline transmission networks outside Kazakhstan and Europe. One pre-requisite for pipeline-based H_2 export in Kazakhstan along the defined route to Europe is an off-shore pipeline section across the Caspian Sea, which - to the date of writing and to the best knowledge of the authors - has so far not been publicly discussed yet. Furthermore, H_2 pipeline agendas in the countries of Azerbaijan, Georgia and Türkiye are not yet fully defined or accessible in order to make a solid evaluation how feasible the scenario of a pipeline connection among those countries can be in the end. It must be pointed out that transit tariffs for cross-border transmission in the respective transit countries are not included in the indicated cost figures.

To decrease the level of dependancies on future partner countries and respective stakeholders involved H_2 transport can potentially by-pass the country of Türkiye if H_2 pipeline transmission ends at a Black Sea port in Georgia, i.e. Poti or Batumi. For this option, H_2 would have to be converted first to NH_3 or LH_2 nearby the respective export port. As an alternative, NH_3 can be delivered via tankers across the Caspian Sea and via pipeline across Azerbaijan and Georgia to a Georgian Black Sea port. From there NH_3- or LH_2-tankers can be loaded for the last route-section and finally deliver a green product to Europe via international waterways. What is of advantage of this option, is the increased flexibility regarding the port of destination for NH_3 or LH_2 unloading as respective tankers would not be restricted to European Black Sea ports such as Burgas or Constanta due to the access to the Mediterranean Sea and the Atlantic ocean via marine straits Bosporus and Gibraltar. On the other hand, process steps in the supply chain for NH_3 or LH_2 conversion (as well as H_2 re-conversion if required) and associated efficiency losses can lead to higher transport costs when partly shipping the product to Europe compared to pipeline transmission via Türkiye. The effect on cost increase due to NH_3 conversion can be slightly mitigated if NH_3 production takes place in Kazakhstan which is assumed to provide for low electricity prices - and hence production costs - in the future compared to other countries along the Middle Corridor. Also, cost reductions for the final product can be additonally achieved, when NH_3 is not subject to re-conversion at the European import ports. If and to what extend green NH_3 as a final product can be an attractive alternative to green H_2 depends among other things on the willingness-to-pay for H_2 and actual demand for NH_3 in the target markets.

Main findings are:For the Small scale use case in 2030 both H_2 export exclusively via pipelines, as well as NH_3 export via a combination of NH_3 tankers and intermediate NH_3 pipeline transmission are competitive from a cost perspective with a slight advantage for H_2 export via pipelines

- For the Large scale use case in 2040 the assessment suggests H_2 transport via pipelines, rather than transport by ship.
- As an alternative to pipeline transport via Türkiye the pipeline tranmission could end at Georgian Black Sea ports. From there shipping of NH_3 in the Small scale use case in 2030 shows lower transport-associated costs (i.e. conversion, shipping, re-conversion) compared to LH_2. The option of LH_2 can outcompete NH_3 by 2040 if, for example, electricity costs for conversion and re-conversion decrease over time and provided that respective ship types are available by then
- NH_3 transport via rail is considered not feasible due to the immense need for infrastructure development of rail networks and fleet expansion in the light of the large volumes of NH_3 assumed in the assessment as well as lacking permission for the transport of hazardous goods below the Bosporus through Türkye via the Maramary tunnel.
- It is critical to point out, that the transport assessment of the study at hand did not take into account intermediate project developments during the scale-up phase, in which transport volumes are of much lower magnitude in the beginning and increase over time. Such scale-up use cases were not defined for this study and accordingly the findings of this study might not be applicable for a scale-up scenario. Thus, the option of rail transport during the scale-up phase, e.g. via alternative routes across Russia must not be discarded and are advised to be investigated in additional studies.

05

Conclusion

5 Conclusion

Today the Middle Corridor is an established and strongly used transport route to deliver various goods mainly via rail between Kazakhstan and South-East Europe. In the light of future large-scale H_2 production in Kazakhstan this transport route can embody a solution to export green H_2 to Europe, where the demand for H_2 is high and domestic production potentials are limited.

Within Kazakhstan an extensive pipeline transmission network for both natural gas and crude oil, as well as an extensive railway network is in place. As for the pipeline network, its' utilization beyond fossil fuel transmission is feasible due to the option of repurposing respective pipelines for the transport of H_2. Which pipelines can be dedicated for domestic pipeline transmission strongly depends on the location of future H_2 production sites, demand locations and export points, as well as the "H_2-readyness" of nearby pipelines and future relevance for fossil fuel transmission and respective availability for H_2 transport. Alternatively, new pipeline systems can be established to foster a strong H_2 economy within the country of Kazakhstan. In the light of large transport volumes, pipelines embody a cost-effective and efficient way of transport, compared to other forms of domestic transport such as via rail.

Looking at the given infrastructure that is in place along the Middle-Corridor outside Kazkahstan, new transport concepts must be developed if large-scale H_2 transport is to be established in the future. The undertaken assessment in this study suggests H_2 transport via pipelines and dedicated NH_3-tankers, rather than transport by rail. This is mainly due to the immense need for infrastructure development of rail networks, fleet expansion and the large volumes of final products subject for export.

The delivery of H_2 from Kazakhstan to South-East Europe exclusively via pipelines show slight advantages from an economic point of view. However, uncertainties remain which concern the availability and capacities of future pipeline transmission networks outside Kazakhstan and Europe. The option of shipping to increase flexibility regarding the final destination for import - and simultaneously decrease the level of dependancies on future partner countries - H_2 pipeline transmission could end at a Black Sea port in Georgia. As an alternative, NH_3 can be already produced in Kazakhstan at low costs and exported via tankers across the Caspian Sea and via pipeline across Azerbaijan and Georgia to a Georgian Black Sea port. From there respective ships for big-scale transport can be loaded again and finally deliver a green product to Europe via international waterways.

The undertaken study focused on techno-economic aspects of different H_2 transport options along the Middle Corridor. Any transport concept will require the involvement of several partner countries and stakeholders along the respective route sections. Accordingly, the feasibility of future partnerships must be assessed further as such an evaluation was beyond the scope of this study.

06

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07

Appendices

7 Appendices

7.1 Technical Configuration of Pipeline Transmission Networks

Pipeline system description

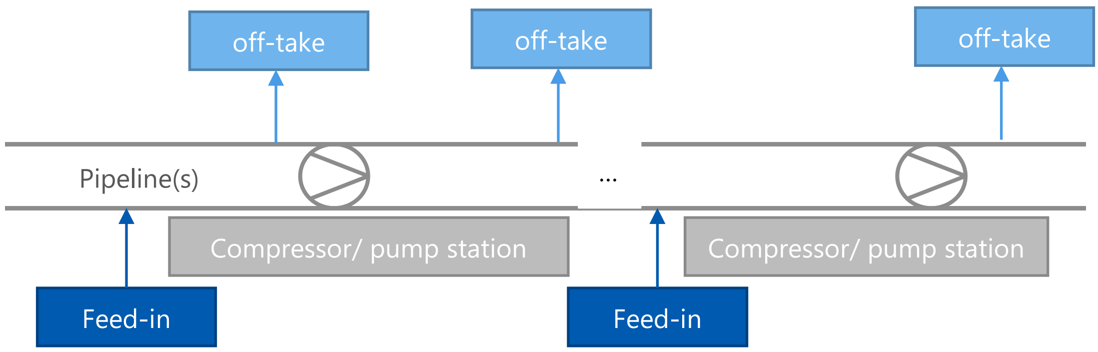

Figure 29: Schematic pipeline transmission system

Due to the spatial distance between the production sites (*'Upstream'*, e.g. oil and natural gas production) and respective demand locations ('Downstream', e.g. refineries, industrial areas, distributional natural gas networks), the respective medium subject for transport (e.g. crude oil or natural gas) can be delivered via pipelines (*'Midstream'*).

The transport via pipelines shows several advantages compared to other transport options (e.g. rail or ship) and can be a cost-effective way even for large transport distances (i.e. several thousand km). An efficient design of a pipeline transmission system combines the following benefits:

- delivery of large volumes on a regular basis
- low energy losses
- simultaneous supply of multiple off-takers
- transport distances on a local, as well as trans-regional scale feasible
- in the case of the transport of gases, pipelines can be used as a temporary storage system (so-called line pack) in order to balance temporary differences between feed-in (i.e. supply) and off-take (i.e. demand)

Besides pipelines, compressor stations (for natural gas transmission) or pump stations (for crude oil) are deployed in a pipeline network to maintain the operating pressure (OP) of the transported medium and compensate for pressure losses over the transport distance.

Compressor stations (for gas) / pump stations (for oil)

State-of-the-art natural gas compression in transmission networks is realized by the operation of so-called turbo compressors which are driven by a gas turbine in which natural gas is combusted. Turbo compressors take advantage of the centrifugal force of the medium subject for compression. In the case of natural gas, the so-called compression ratio (i.e. discharge pressure at the outlet over suction pressure at the inlet) is usually set to 1.4 (e.g. 100 bar discharge pressure and 70 bar suction pressure) which allows for a cost-effective compressor operation. Average distances between such compressor stations in a transmission network typically vary between 100 km and 400 km. In the case of oil transmission, centrifugal pumps are commonly applied for large transport volumes. Several pumps can be installed in parallel or series.

For large transport volumes and to allow for redundant configurations several compressor or pumping units are installed within one compressor or pump station. Depending on the use-case at hand economics will determine the number and size of the units in each station. The following figure shows a multiple unit compressor station for natural gas.

Figure 30: multiple unit compressor station [50]

7.2 Excursus: Repurposing of Natural Gas Pipelines for Hydrogen

The systems originally designed for natural gas transport can pose limitations in certain areas as previously explained. Therefore, another option can be considered which is the repurposing of the system for pure H_2 transport.

Some technical guidelines have already been published for the retrofitting of the natural gas network into pure H_2. This includes the German standard DVGW Code of Practice G 409 which provides the general requirements in terms of the required testing and reviews to establish the suitability of the pipeline to be repurposed for H_2. These requirements mainly include but are not restricted to material testing, pressure testing, inline inspection, and others. This document also refers to ASME B31.12 which is the most adopted technical standards for H_2 pipelines.

The latter provides the section PL-3.21 dedicated to steel pipeline conversion where among other steps, two design options are presented to ensure the material qualification of the pipe:

- Option A (Prescriptive Design Method): This option call for the compliance of the material according to the chemical and tensile requirements of API 5L Product Specification Level 2 (PSL2). Additional testing is also required to evaluate brittle fracture control and ductile fracture arrest. Welds as well as heat affected zones (HAZ) shall be qualified with Charpy tests. This option A would also limit the operating pressure by a factor of 0.5.
- Option B (Performance-Based Design Method): This is the typically recommended option as it can allow a higher design factor for the pipeline compared to Option A (0.72). All API 5L PSL2 requirements shall be met. Fracture mechanics analysis is implemented within this option based on H_2 charged samples from destructive collecting.

It is worth mentioning that in practice, ASME B31.12 might be considered relatively conservative by many experts. Depending on the specific cases, the certification and permitting authorities may deviate slightly from it after thorough assessment of the age and current condition of the pipeline as real life examples of repurposing projects in Germany show. Generally speaking, there is not one specific way to follow when making such evaluations and it strongly depends on requirements defined by the permitting body that assigns a final approval.

Several European projects that aim to repurpose existing natural gas pipelines for H_2 transport are already underway as part of the European hydrogen backbone initiative. The following are some examples:

- In Germany, the project of Energie Park Bad Lauchstädt will include the conversion of 7,7 km gas pipeline to pure H_2. It is expected to operate at 30 bar (MAOP 63 bar) in the first quarter of 2024. [61]
- Again in Germany and more specifically in Bavaria, Bayernets is repurposing a segment of pipeline of their planned H_2 network as part of the Hypipe Bavaria Project. The project is planned to be finalized by 2030. [62]
- In France, GRTgaz is converting 70 km of existing natural gas pipelines, some of which were abandoned to H_2 as part of the project mosaHYc [63].
- In Denmark, Energienet has started the process of requalification and material testing of 93 km of its natural gas pipelines to be repurposed for H_2 transport [63].

- In the UK, Nationalgrid is developing a dedicated H_2 transmission network which repurposes several parts of its existing natural gas infrastructure. This conversion is expected to be sequentially finalized between 2027 and 2032. [63]

As a concluding remark for the prospect of repurposing natural gas pipelines for H_2 transport, the following points can be made:

- A comparison between the given pipeline material of an existing pipeline segment and the materials considered to be "H_2-ready" (with reference, e.g. to the literature of [64] [65] [66]) can be used to already rule out pipelines from a material point of view. For example, in Germany most natural gas pipelines being considered compatible for H_2 applications
- Apart from the material aspects, the physical condition of a given pipeline is critical for an evaluation. Especially unprecise and inadequate welding seams can embody an increased risk for H_2 embrittlement. State of the art pipe laying and welding makes use of weld automats which provide best quality welding seams. However, when investigating existing pipelines of recent decades manually welding in the trenches could have been applied and according welding seams could be of limited quality. The applied welding technique should be documented in respective pipeline records
- Pipeline inspection of the state of fitness of a given pipeline with a camera is recommended in any case. In that way, suspicious welding seams - for example due to manually welding technique at the date of construction - can be evaluated more thoroughly. Additional coating can be applied to mitigate the risk of H_2 embrittlement of the material on the inside of a pipeline, ultimately allowing for higher OP in some cases.
- With regards to applied operating pressures (OP) in a H_2 scenario, formulas of the framework of ASME B31.12 can be used. A general comment cannot be made here, as applicable OP depends on sevral parameters, e.g. wall thickness and pipeline material. Accordingly, a case by case evaluation must be undertaken
- Further measures as part of the overall repurposing process can the purging of the pipelines and the replacements of valves if required. Obviously, other network installations which will be in physical contact with the medium H_2, e.g. metering or regulating stations must be analyzed for its' H_2 readiness

It must be pointed out, that when looking at a pipeline transmission system, also all the 'non-pipeline' equipment must be examined for their H_2-readyness. This is particularly relevant in the case of compressors as in the case of pure H_2 transport, the compressors used for natural gas transmission are expected to be replaced by H_2 compressors due to the different chemical properties of H_2 compared to natural gas.

7.3 Deep Dive: Rail and Ship NH_3 Transport Options across the Caspian Sea

Ammonia rail transport by wagon load

NH_3 in bulk is an established commodity for rail transport. For example, private wagon lessors provide appropriate rail wagons for lease with a volume capacity of approx. 100 m^3 (see Figure 31).

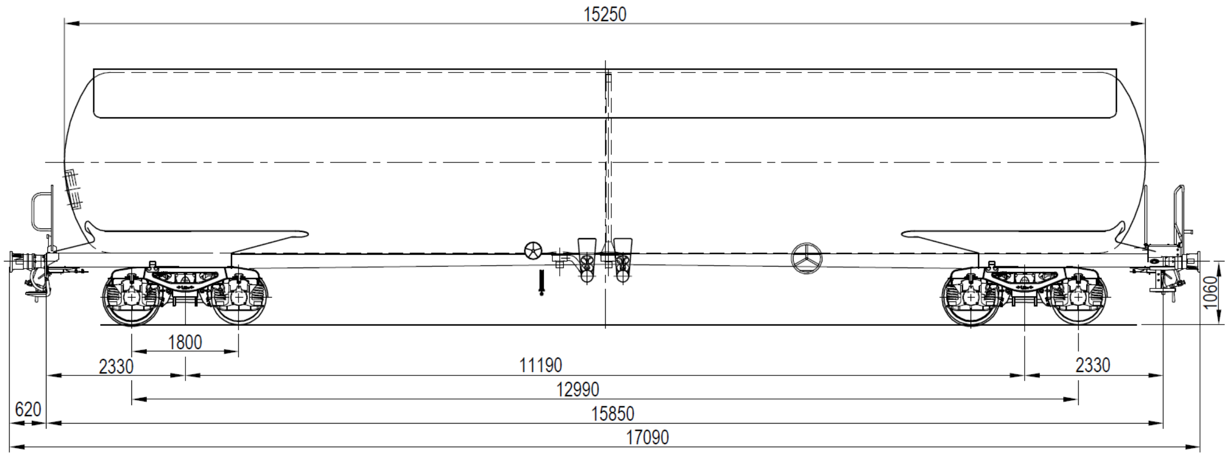

Figure 31: Tank rail wagon suitable for ammonia. Source: VTG

This type of wagon would provide a capacity of approx. 56 t/wagon load given 22.5 t/axle weight restrictions (European D4 track standard). As such, a target production volume of 1 Mtpa in the "Small scale" case would require appr. 18,000 wagon moves per year. Considering the required empty positioning assuming no suitable return cargoes, the rail corridor needs to have a capacity for some 36,000 wagons moves per annum; and an eleven fold increase is to be considered once the "Large Scale" case should kick in in 2040 (11 Mtpa).

Ship

Above´s requirement poses some challenges for the rail ferry services across the Caspian Sea. Although, from publicly available air photography, the port infrastructures on both the Azerbaijan and Kazakh-side appear suitable, it is questionable whether there is sufficient rail ferry capacity.

The Port of Aktau provides the following information on the ferry crossing Baku-Aktau-Baku [11]:

- Distance – 253 nautical miles
- Traffic capacity – 2 Mtpa
- Time of ferry travelling – 18 h.
- Time of ships' handling – 8-10 h.
- Restrictions on ship draft – 5.1 meters

Another regular ferry service has been established between the ports of Kuryk and Alat (Baku), which are located at a distance of 244 miles (approximately 452 km) from each other, which allows delivering cargo in 18 hours (for example, a ferry from the port of Aktau to the port of Baku is on the way 22 hours). Port Kuryk is a partner in the project on establishing a corridor for effective cooperation from the Baltic coasts to the eastern shores of the Caspian Sea coordinated by the Baltic-Black Sea Economic Forum, as well as – in the Global Multimodal Logistics project. [78]

These ferry services are operated by Azerbaijan Caspian Shipping Company (ASCO) using ferries of the type of MV "Profesor Gul" (see Figure 32) with a transport capacity of just 54 rail cars (or a similar number of trucks) or 3,900 tdw in total.

Figure 32: Typical rail ferry of ASCO. [93]

Currently, ASCO gives for 2022 appr. 38,600 rail wagon moves and 35,000 truck shipments across its network. [79] Based on above´s transport requirements of 36,000 rail wagon moves, this would almost double the current rail-related transport volume of ASCO[21], even for the "Small scale" case only, which we consider unrealistic.

A slightly more positive picture emerges looking at rail ferry handling capacities in the ports. The Port of Aktau gives as its annual capacity 2 Mtpa, and the Port of Kuryk a design capacity of 10 Mtpa. [11, 12] The project under scrutiny would require 3.6 Mtpa (=36,000 wagons @ 100 t/wagon including own wagon weight) of that total amount of 12 Mtpa on the Kazakhstan-side. At Azerbaijan, the Port of Alat advertises as overall cargo throughput at the new Port of Baku at Alat 10–11.5 Mtpa of general cargo and 40,000–50,000 TEU p.a.

The latter figure suggests an alternative, which would be to load the NH_3 into LPG-capable tank containers, which in turn are loaded on appropriate flat-bed rail wagons to/from the ports, and using regular container vessels to provide for the maritime section. For this alternative, the similar capacity considerations as above apply in terms of transport capacity and the need to empty reposition the container equipment as a similar number of containers as rail wagons are required, which needs to be compared to the advertised capacities of the terminals.

[21] Including connections to Turkmenistan.

A consideration would be to mix rail and containerised transport options, but still, the required transport volumes to be made available both on rail as well as on container vessels (as well as in the relevant port terminals) pose formidable challenges for the existing infrastructure, as dose the return of the empty equipment.

A third alternative would be to use rail wagons as above to/from the ports and load the cargo onto specialised LPG-vessels for the crossing of the Caspian Sea. All of the options above either need at least some expansion of the ports´ rail ferry infrastructure or new vessels, or both. It is questionable whether especially the latter can be achieved in sync with the project´s time horizon and without substantial input from Russia, in terms of providing ship yard or inland waterway capacity (see below).

7.4 Excursus: Ammonia via Ship

The synthesis (Haber-Bosch synthesis), as well as the storage and shipping of NH_3 are mature technologies. More precisely NH_3 is an internationally traded chemical. As such, large-scale NH_3 transport is a well-established business all over the world. The main challenge of NH_3 as transport vector for hydrogen is the NH_3 cracking, which means the reconversion of NH_3 to hydrogen (see Figure 33). The process is energy intense and, to date, not an established technology.

Figure 33: Ammonia transport value chain

Conversion

Figure 34 shows a schematic illustration of NH_3 production from H_2 and N_2. Firstly, H_2 and N_2 are compressed before mixing with the recycled gases. The mixed gases (H_2, N_2 and recycled synthesis gas) are preheated and fed into the Haber-Bosch synthesis reactor. After the reactor, the effluent is cooled and fed to a vapor/liquid separator to separate NH_3 product from unconverted gases. The unconverted gases are recompressed and recycled. The NH_3 is sent to a refrigeration system to enable a storage as “fully refrigerated” liquid.

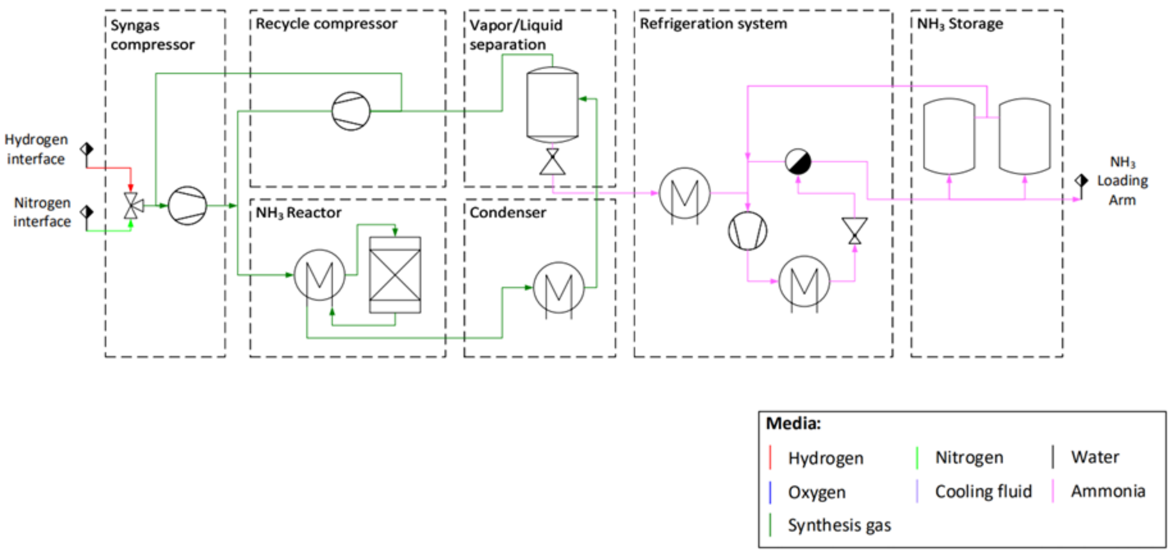

Figure 34: Simplified process flow diagram for a ammonia synthesis and export facility

Shipping

Figure 35 shows the 2017 status of international NH_3 import (red dots) and export (blue dots) facilities as well as the transport routes. The colours of the transport dots show the frequency liquid NH_3 carrier are using the individual route.

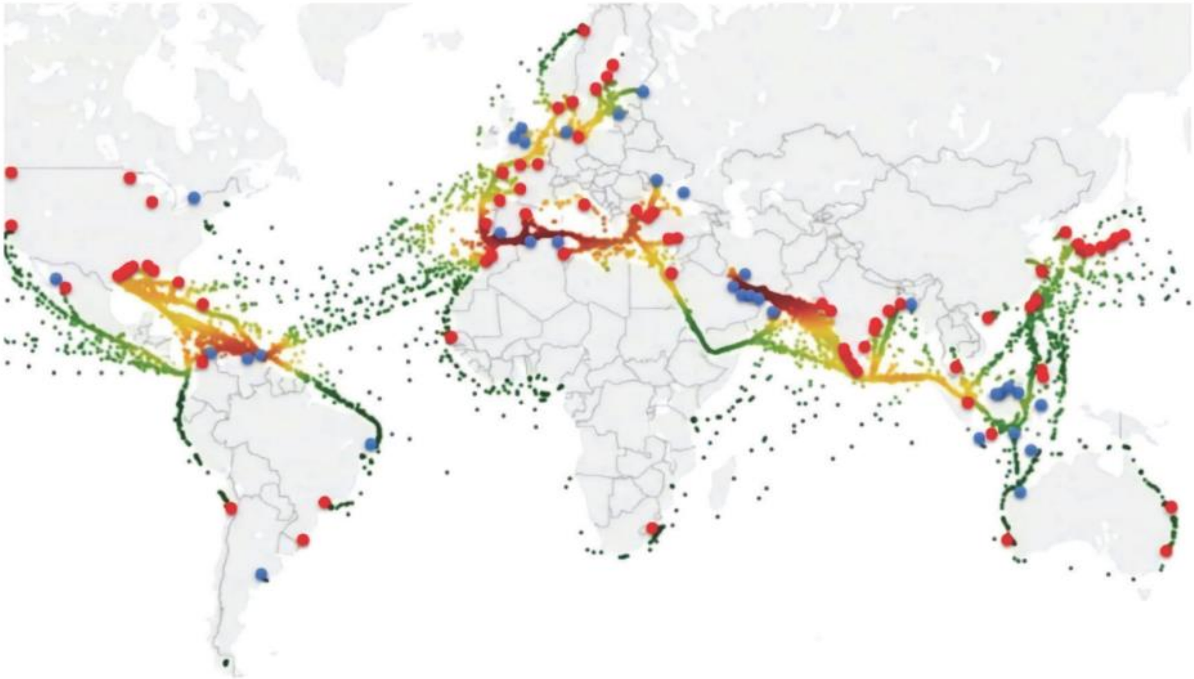

Figure 35: Ammonia shipping infrastructure, including existing Ammonia port facilities (2017) [80]

The shipping of NH_3 is usually done in the state "fully refrigerated" which means at ambient temperature and ~ -33°C. This most cost-efficient transport state enables the usage of LPG carriers, where todays max. capacities are in the range of 83,000 m³ per vessel (VLGC). Also smaller carrier such as handy size gas carrier (HDY / HGC; ~20,000 m³), medium gas carrier (MGC; ~38,000 m³), and large gas carriers (LGC; ~60,000 m³) are available on the market and today usually used, since the transport capacities are not large enough to justify larger vessel sizes.

Apart from using LPG carriers, the option of loading multiple standardized containers embodies an alternative form of containment from a technical point of view. Respective NH_3 containers are comparable to the containers used for rail transport. In the event of absence or unavailability of respective LPG carriers in the Caspian Sea, NH_3 shipping could be realized by using container vessels. However, both the practicability and the profitability of such a transport concept will highly depend on upstream and downstream logistic chains and port (un-) loading capacities.

Reconversion

The NH_3 cracking process is expected to be based on the NH_3 synthesis process, but operated on lower pressures (e.g. 20-40 bar, instead of 50-300 bar for the synthesis) and slightly higher temperatures (up to 900 °C for cracking compared to 600 °C for synthesis) to reverse the conversion process. After the reconversion of NH_3 to H_2 and nitrogen the remaining syngas is separated in a pressure-swing adsorption (PSA) to generate a pure stream of H_2 (see Figure 36). The remaining flue gas (nitrogen + H_2 + NH_3) of the PSA will be used together with parts of the NH_3 input to fuel the process.

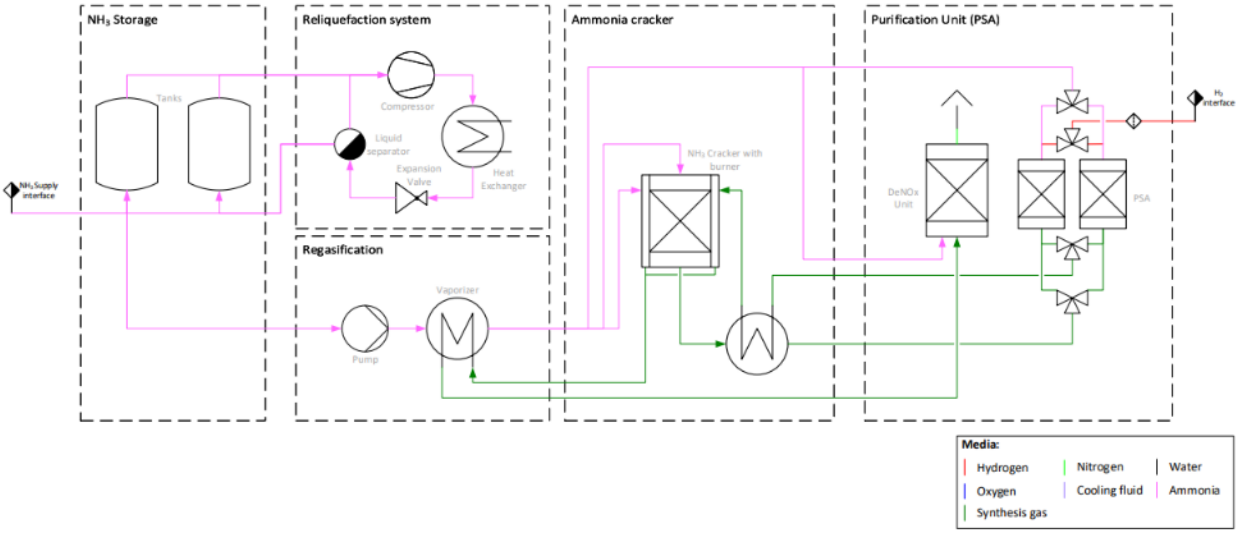

Figure 36: Simplified process flow diagram - ammonia storage and cracking

Although today no OEM is capable to deliver an NH_3 cracking plant there are multiple companies investigating the technology:

- ThyssenKrupp
- Johnson Matthey
- Linde (together with Saudi Aramco)

7.5 Excursus: Liquid Hydrogen Transport via Ship

The liquefaction, storage and regasification of liquid hydrogen are mature processes for small scale applications (up to 30 TPD). The most critical part of the liquid hydrogen transport value chain is the shipping itself.

Figure 37: Liquid hydrogen transport value chain

Conversion

Figure 38 shows a simplified process flow diagram for a liquefaction and export facility of liquid hydrogen. Hydrogen from e.g., an electrolyser or a pipeline must first be cleaned to very high purity levels before it can be liquefied. The purity is required as any contaminants would freeze at the extremely low temperatures reached in the subsequent liquefaction, which would have negative effects on the process.

The hydrogen stream must then be cooled down to liquefaction temperature (20 K) and stored before it is transferred to the LH_2 ships. This is done with a pre-cooler to reach a temperature of approx. -80°C to -160°C, which is below the inversion temperature of hydrogen (200K), which then enables to cool the hydrogen like a common refrigerant.

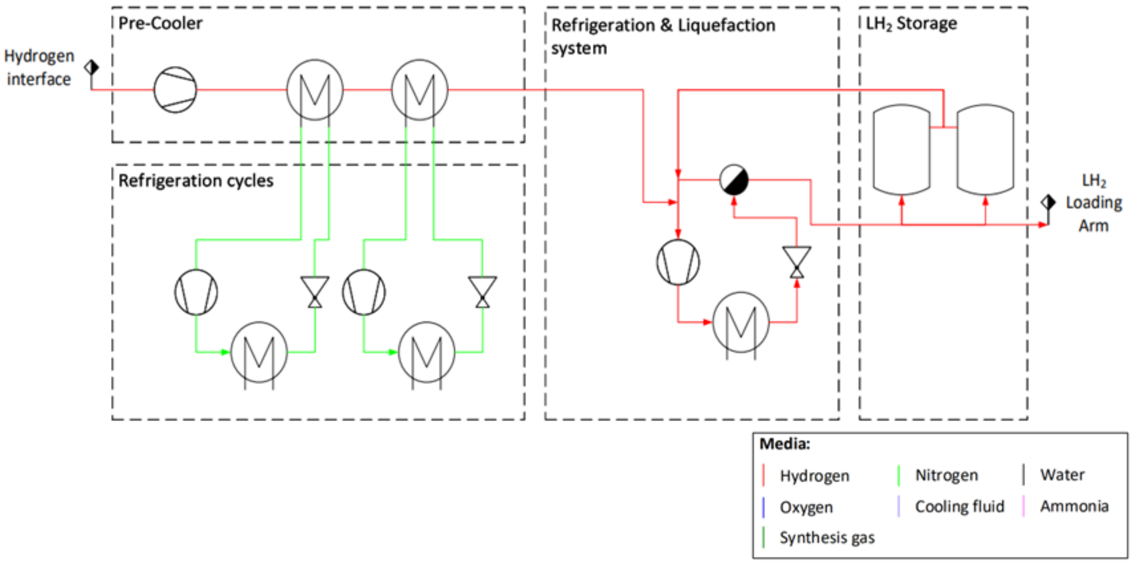

Figure 38: Simplified process flow diagram for a liquefaction and export facility

Shipping

Today shipping of liquid hydrogen does not exist on a commercial scale. Kawasaki has a pilot project running with a capacity of 89 tons of hydrogen.

Figure 39: Pilot project for liquefied hydrogen shipping

Although the largest vessel manufacturer in the world (Kawasaki Heavy Industries, Samsung Heavy Industries, KSOE) are very interested in the production of the vessel the development of a commercial product is still challenging. The extremely low temperatures (even for cryogenic systems) are leading to challenging design problems for the storages as well as the safety equipment.

The aim of the vessel manufacturers is to develop multiple sizes of LH_2 carriers, starting with commercial vessels with a capacity of e.g. 20,000 m³ / ~ 1,600 t. On the medium to long-term future common LPG and LNG carrier sizes of 80,000 and 160,000 m³ / 6,320 t and 11,230 t per vessel are the expected vessel sizes also for LH_2 vessels.

Interesting for short distance transport of liquefied hydrogen may also be the interest of some companies to develop RoRo vessels, that use common LH_2 trailer as storages for the hydrogen. Nevertheless, based on Fichtner's market view these systems won't be able to achieve substantial economies of scale which will lead to high overall transport costs, if the LH_2 trailer cannot be used to develop hydrogen directly to the end users.

Reconversion

The reconversion of liquid hydrogen is an easy and mature process. As same as for LNG LH_2 can be regasificated in open-rack vaporizer using ambient heat supplied by air, seawater or industrial waste heat.

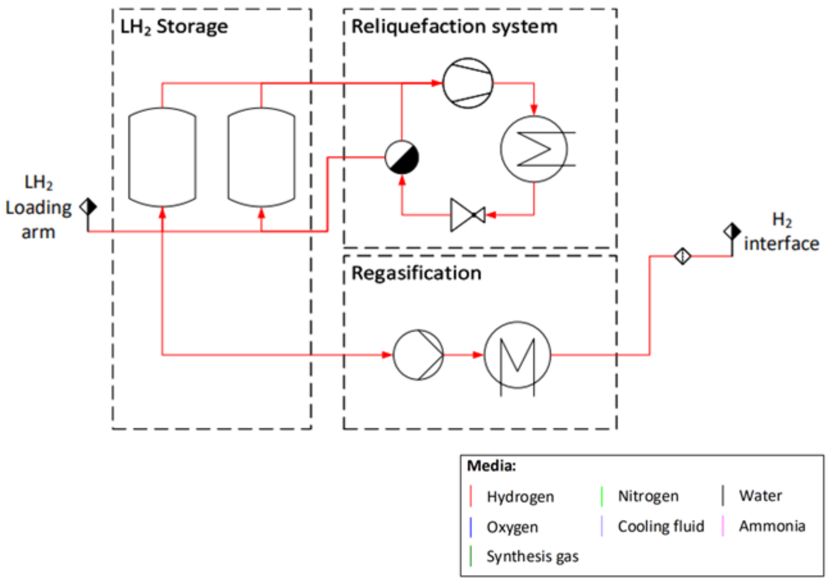

Figure 40: Simplified process flow diagram for a LH_2 import and regasification facility

7.6 Excursus: Compressed Hydrogen via Ship

The compression, storage and reconversion / recompression of gaseous hydrogen are mature processes. The most critical part of the gaseous hydrogen transport value chain is the shipping itself. Today no GH_2 vessel has ever been built to ship hydrogen.

Figure 41: Gaseous hydrogen transport value chain

Conversion

The word “conversion” is not applicable for the gaseous transport value chain, since there is no change in its form. To charge the vessels the hydrogen does only need to be compressed to approx. 250 bar_g. The advantage of this process compared to any kind of synthesis or liquefaction is its easy and flexible process. Unfortunately, the gaseous state does also mean that the product is challenging to store. This means that it is likely that at least 1 offtake vessels is permanently required in the export facility to work as “storage” under a ”drop and swap” charging strategy.

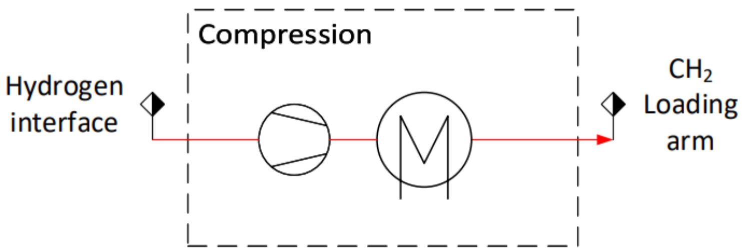

Figure 42: Simplified process flow diagram for a GH_2 compression and export facility

Shipping

Today shipping of gaseous hydrogen does not exist. Provaris, formerly known as GEV, is developing as only OEM a ship that can transport gaseous hydrogen with a pressure of up to 250 barg.

Figure 43: Developing GH_2 vessels with a capacity of up to 2,000 t by Provaris, formerly known as GEV

The aim of the vessel manufacturer is to develop 2 sizes of GH_2 vessels. One with a capacity of approx. 26,000 m³ / ~ 430 t and a larger one with a capacity of up to 120,000 m³ / 2,000 t. Since the hydrogen transport capacities are comparably low compared to other hydrogen derivates, the shipping does require much more vessels.

As of today (Q1/2023) Provaris has got a "Approval for construction" and states it is under negotiations with Asian vessel manufacturer to build a pilot vessel [81].

Reconversion

The reconversion of gaseous hydrogen is a very easy process. The vessels are discharged via natural flow and afterwards emptied with common hydrogen compressors (see Figure 44). Since the hydrogen is not chemically treated, the outgoing hydrogen quality is expected to be the same as the input quality.

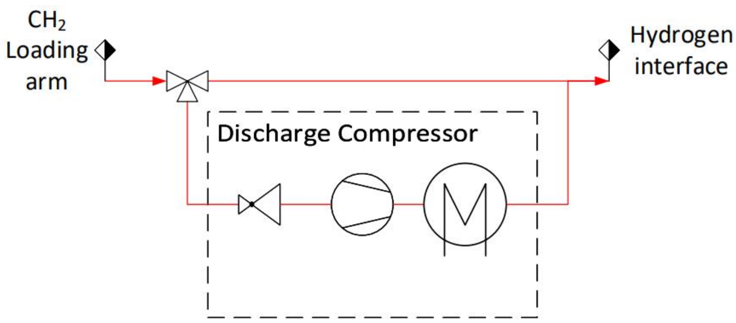

Figure 44: Simplified process flow diagram for GH_2 reconversion

7.7 Excursus: Long-term inland Waterway Option

An inland waterway from the Caspian Sea to the Black Sea would provide for yet another alternative, such as various ideas of canals to be built between the two "Seas", such as the Eurasia-Canal, the Manych-Canal or the Volga-Don-Canal (see Table 22). Although two are still in projecting stage, or only partially completed, they provide for interesting thought experiments, as such that these canals might be used by combined inland/sea-going vessels[22] plying from Kazakhstan to (European) ports of the Black Sea, from which the cargo can be shipped by NH_3-tanker to international destinations, or by inland vessel (along the River Danube) or rail to European destinations.

Canal project	**Volga-Don-Canal**	**Manych-Canal**	**Eurasia-Canal**
Description	Opened in 1952, it connects the Volga and the Don at their closest points with a length of 101	Linking the Sea of Azov and the Caspian Sea the 700 km-long Manych Ship Canal project includes the	A proposed 700-kilometre-long canal along the Kuma-Manych Depression. Currently, a

[22] As customary on the River Rhine in trades to the UK or other European destinations (short sea shipping) with payloads of up to 3,000 tdw.

Canal project	Volga-Don-Canal	Manych-Canal	Eurasia-Canal
	km, 45 km (28 mi) of which is through rivers and reservoirs. The canal forms a part of the Unified Deep Water System of European Russia. Together with the lower Volga and the lower Don, the canal provides the shortest navigable connection between the Caspian Sea and the world's oceans via the Sea of Azov, the Black Sea, and the Mediterranean Sea. It uses nine single-chamber canal locks on the Volga slope to raise and lower ships 88 m, and four canal locks of the same kind on the Don slope that raise/lower ships 44 m from river height. The maximum allowed vessel is 141 m length, 16.8 m beam, and 3.6 m draught (the Volgo–Don Max Class) resulting in 5,000 t cargo capacity.	existing Manych Waterway through Lake Manych-Gudilo and the Veselovskoe and Proletarskoe reservoirs, and could be extended to the Caspian Sea via the sparsely populated steppes of Kalmykia. Proposals are being considered to turn it into a larger form known as the Eurasia Canal (see right column). A proposed design would deepen the canal to 6.5 m and widen it to 80 m (vessels of 10,000 t design capacity).	chain of lakes and reservoirs and the shallow irrigation Kuma-Manych Canal are found along this route. The canal is intended to provide a shorter route for shipping than the existing Volga–Don Canal system of waterways; it would also require fewer locks (or lower-rise locks) than the Volga-Don route. From the confluence point of the West Manych and the Don, the ships would follow the same route as used by the existing Caspian-to-Black Sea navigation, i.e., less than 100 km down the Don until its fall into the Sea of Azov, and then across the Sea of Azov and the Strait of Kerch into the Black Sea.
Status	Operational	Projected	Proposed
Problems	Crosses Russian territory	Crosses Russian territory Construction of locks required, and water supply to maintain sufficient water depth.	Crosses Russian territory Construction of locks required, and water supply to maintain sufficient water depth.

Table 22: Overview of canal projects linking the Caspian Sea with the Black Sea. Source: Wikipedia

As all canals cross Russian territory, those are deemed excluded from the scope of this study. Due to the long time horizon to implement such infrastructure projects (some of them have been around since the 1940eis), those are not considered serious alternatives.

7.8 Excursus: NH_3-vessel Availability in the Caspian Sea

Option 1: Newbuild from outside of Caspian Sea area sized to fit Volga-Don-Canal

In order to address the bottleneck of vessel availability on the Caspian Sea, shipbuilding outside of this area might be considered, requiring the new-builds to be transported from the shipyard to the Caspian Sea.

As we pointed out, the Volga-Don-Canal connects the Volga and the Don at their closest points with a length of 101 km. The maximum allowed vessel features a length of 141 m, a breadth of max. 16.8 m, and a draft of 3.6 m (the Volgo–Don Max Class) resulting in 5,000 t cargo capacity. These particulars resemble the dimensions of typical vessels plying the Caspian Sea (see Figure 45: length of 139, breadth 16 m, draft 4.7m, 6,200 tdw., or L 108 m/B 16 m/D 4.8m, 5,500 tdw.) reflecting the maximum allowable vessel sizes for typical Caspian Sea ports.

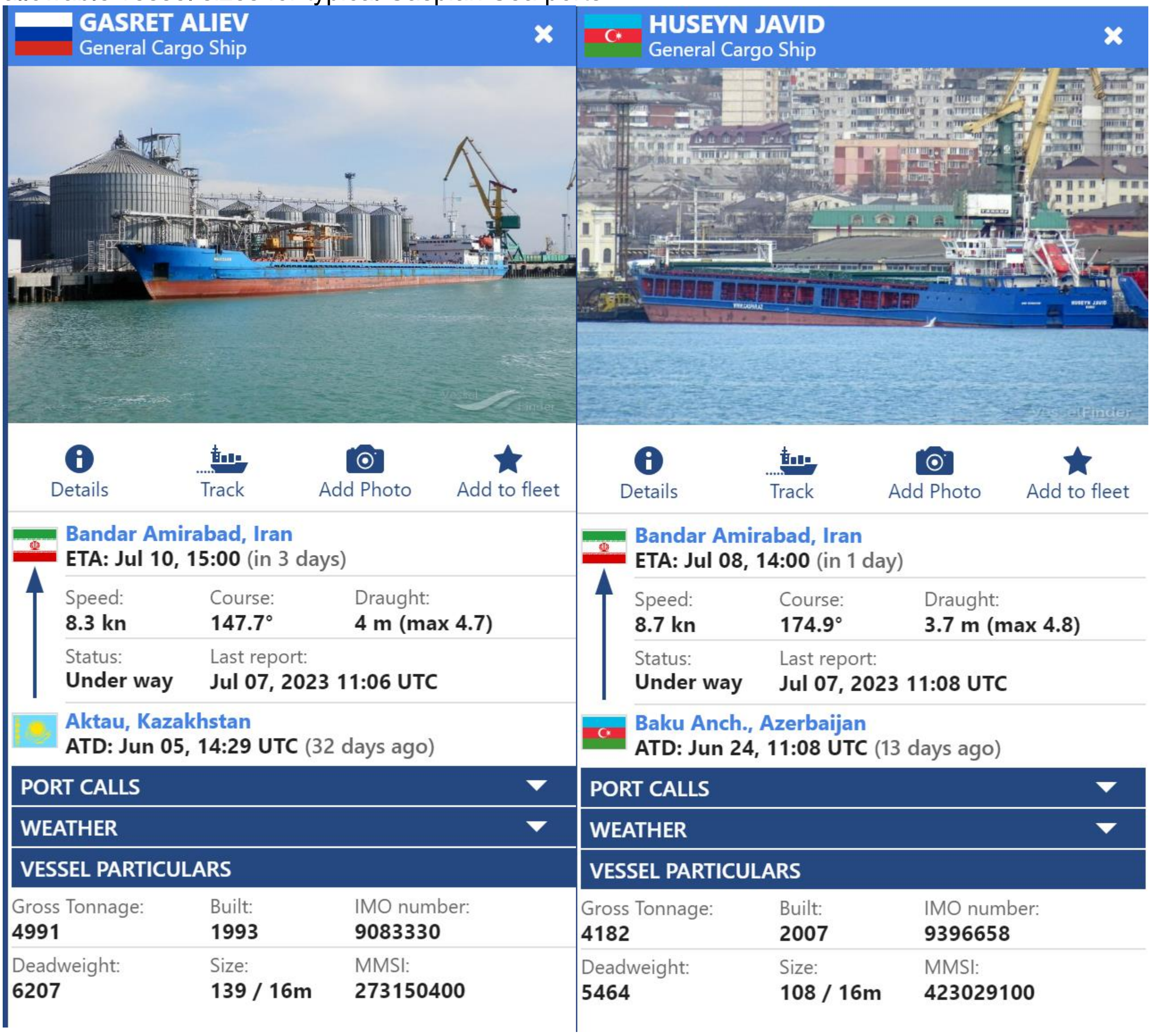

Figure 45: Example of vessels in the Caspian Sea. [86]

As empty vessels draw considerably less than 4.7m (as per above´s example the actual draughts are 4.0m and 3.7m respectively) we deem it technically possible to meet the size restrictions of the Volga-Don-Canal so as to build required LPG-tankers elsewhere and position them empty via the canal into the Caspian Sea.

Option 2: Partly-assembled newbuild from outside of Caspian Sea

As the LPG-tankers would be regularly deployed between two defined ports that can handle ammonia, the available depth could be utilised in full. Table 23 shows the current depths of the oil berths at the three ports considered above for rail and container shipments, namely Aktau and Kuryk on the Kazakh side, and Atal on the Western shore.

Table 23: Max. depth at selected regional ports. [78, 87, 88]

Port	Advertised max. depth at oil berth (if available) [m]
Aktau	7.0
Kuryk	8.5
Atal	7.0

Based on a depth of c. 7 m, we might consider vessels with up to 7,000 tdw. capacity to be built. The following examples might provide some guidance, although the vessel sizes are to be considered as high-level guidance only as these are sea-going vessels (Figure 46).

MT SYN ALTAIR ex Val Cadore: LPG – Ethylene Carrier with loading capacity of 7,200 tdw. at a draft of 8.1 m featuring a length of 115.3 m, and a beam of 16.8 m (pictured left)

MT BRIGHT HONOR: LPG TANKER with a loading capacity of 7,246 tdw. on 7,610 m draft, length of 113.6 m, beam 16.5 m (no picture)

Figure 46: Small LPG tankers (examples). [89]

Those vessels will need to be shipped in parts from shipyard to the Caspian Sea. This might be achieved by means of loading respective parts on unpropelled barges and push/tow them as appropriate through the Volga-Don-Canal. At the Caspian side this requires experience yard capacity to assemble the vessel parts meeting the quality standards of the shipyard. If you can find a shipyard inside the Caspian Sea to be able to carry out these tasks, most probably this yard can also build a new tanker from scratch. Further, this kind of transport requires an additional sea transport from the shipyard to the entrance of the Volga-Don-Canal including lifting capacity to transfer the parts from vessel to barge. This could be achieved by "slicing" the vessel across or over its full length, or a combination of both, bearing in mind that today vessels are assembled in "segments" rather than built from its keel upwards. It needs to be pointed out that we cannot verify the technical feasibility of this, not only in terms of above´s requirements, but also in terms of air clearance concerning fixed bridges over the canal.

The following figures illustrate a normal sea- and river transport of complete or partly assembled vessels (Figure 47).

Figure 47: Sea transport of ferries or docks by semi-submersible vessels. [90]

According to a similar principle, deck-barges are employed to move large engineering structure along inland waterways (see Figure 48).

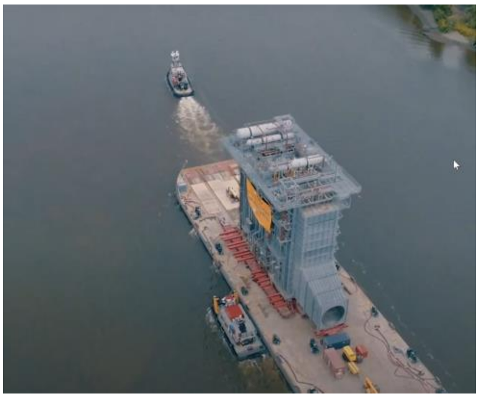

Figure 48: Inland transport of structures by deck-barge. [91, 92]

Option 3: Buying a second-hand dry cargo vessel in Caspian Sea area to refit

Provided competent yard capacity is regionally available, a third option would include buying a second-hand dry bulk vessel in the Caspian Sea area to be converted into a LPG-tanker. For this, we might consider vessels as advertised in Figure 45. Although we sacrifice capacity compared to what might be possible under Option 2, we save the hassle of having to transport (partly-)assembled vessel structures along unknown waterways. Instead, the shipyard might acquire relevant parts, such as pipes, pumps and steel via conventional supply routes.

7.9 Assumptions Cost Estimate domestic Pipeline Assessment

Technical parameters

To find an optimal configuration of a pipeline system, which is defined by

- pipeline size,
- operating pressure (OP), as well as
- compression duties,

a number of assumptions regarding technical parameters must be made. Those assumptions are listed in Table 24.

#	Description	Value	Unit
1	Max. flow velocity	80	m/s
2	Max. operating temperature	10	°C
3	Suction pressure of head compression (Interface 1)	30	barg
4	Discharge pressure of end compression (Interface 2)	80	barg
5	H_2 gas quality[23]	Hydrogen 5.0	-
		99.999	% purity
6	Lower calorific value H_2	3.0	kWh/ m_n^3
		33.3	kWh/kg
7	Density of H_2 at normal conditions (i.e. 0 °C and 1.01325 bara)	0.08988251	kg/ m_n^3
8	Annual operational hours	6,000	h
9	Length of the pipeline route	200	km
		1,000	km
10	Meters of altitude along route	0	m
11	Surface roughness for pipeline diameters <DN 500	100	µm
12	Surface roughness for pipeline diameters >=DN 500	6	µm
13	Construction and installation of pipelines	below-ground	-
14	Weighted Average Cost of Capital (WACC)	8	%

[23] Lower hydrogen purities might be defined for pipeline transmission, e.g. Hydrogen 3.0. Hydrogen 5.0 was assumed due to established purities of the electrolysis process, however, the purity does not affect the system optimization at this level of pipeline assessment

#	Description	Value	Unit
15	Project duration	25	years
16	Fixed OPEX for pipelines	1	% of CAPEX for pipelines
17	Fixed OPEX for compressor stations	4	% of CAPEX for compressor stations
18	Pressure losses are calculated exclusively based on the input parameters mass flow, pipeline diameter, surface roughness, compressor discharge pressure and operating gas temperature. In the field overall pressure losses can be higher due to irregularities in the pipeline flow characteristics such as valves, junctions for off-take and feed-in or change in pipeline diameters, which is typically not considered at such a stage of analyses.		

Table 24: Assumptions for system optimization

Cost parameters

Fundamental for every calculation of costs are the applied specific cost estimates. In the case at hand, those cost estimates are limited to the CAPEX of new transmission pipelines and new compressor stations. Those figures are based on publications both by the European Hydrogen Backbone initiative (EHB) and the Association of Transmission System Operators for Gas e.V. in Germany (FNB), as well as recent market feedback. An overview of the cost estimates is given in Table 25.

Element	CAPEX Cost figure			Unit
Pipelines[24]	DP70	DP80	DP100	
DN400	1.33	1.34	1.35	Mln. USD/km
DN500	1.48	1.49	1.51	Mln. USD/km
DN1200	2.73	2.81	3.05	Mln. USD/km
Hydrogen compressor station				
< 10 MW	5.02			Mln. USD/MW
10 - 20 MW	4.02			Mln. USD/MW
> 20 MW	3.01			Mln. USD/MW

Table 25: CAPEX figures for new infrastructure components of a pipeline transmission system

[24] The design of a pipeline is based on expected operating pressures (OP). When looking for “off-the-shelf” solutions different “categories” of pipelines are established and commonly applied. A pipeline with a so-called design pressure (DP) of 70 bar (80 bar, 100 bar) can be operated up until an OP of 70 bar (80 bar, 100 bar). With regards to costs for those different DP categories, material costs are higher due to increased wall thickness of higher DP.

7.10 Assumptions Cost Estimate via Shipping

The following

Transport value chain	Unit	NH3	LH2
General Assumptions			
WACC for all investments	%	8	
Project duration	a	25	
Indirect cost header	%	30	
Electricity costs			
PoL	USD / MWh	80	
PoD	USD / MWh	100	
Conversion Assumptions			
Spec. direct cost	USD/TPAoutput	360	6,357
O&M	%	5	2
VLH	h/a	8,000	
H_2 consumption	t/tproduct	0.18	1
Electricity consumption	MWh/ tproduct	0.2	7.5
Export facility Assumptions			
Transport value chain	**Unit**	**NH3**	**LH2**
Storage sizing	-	Max (6,25% of throughput and biggest vessel + 8 days)	
Jetty	-	New building	

Direct Costs per Jetty	USD / Jetty	35 Mio.	
Port fees	USD / t	5.25	5
Boil-off	%/day	0,04	0,2
Boil-off handling	-	Reliquefication	Reliquefication
Power reliquefication	MWh/texport	0.2	10
Power vessel loading	MWh/t	0.01	0.01
Spec. direct cost	USD/tstorage	1,316	87,616
O&M	%	4	1.5
Shipping Assumptions			
Density	t/m³	0.68	0.0708
Shipping model	-	Chartered	
Bunker fuel	-	NH3	

Transport value chain	**Unit**	**NH3**	**LH2**
Bunker fuel costs	USD / t	850	
Fuel consumption:			
Laden	tHFO / day	35	81
Ballast	tHFO / day	33	75
Port	tHFO / day	6	5
Boil off handling	-	Used as bunker fuel	Used as bunker fuel
Boil-off	%/day	0.04	0.2

Product insurances	-	Excl.	
Vessel type	-	LGC	LH2 large
time charter rate	USD / day	29,000	152,417
Ballast share	%	100	100
Canal fees	USD	Excl.	Excl.
Import facility Assumptions			
Storage sizing	-	Max (6,25% of throughput and biggest vessel + 8 days)	
Jetty	-	New building	
Transport value chain	**Unit**	**NH3**	**LH2**
Direct Costs per Jetty	USD / Jetty	35 Mio.	
Port fees	USD / t	5.25	5
Boil-off handling	-	Reliquefication	Reliquefication
Power reliquefication	MWh/t	0.2	10
Power Export	MWh/texport	0.01	0.01
Spec. direct cost	USD/tstorage	1,324	105,110
O&M	%	4	1.5
Reconversion Assumptions			
Spec. direct cost	USD/TPAout	2,400	515
O&M	%	5	2.5
VLH	h/a	8,500	
Thermal power supply	-	By transport chain	

Losses	%	22	0
Electricity consumption	MWh / tproduct	0.173	0.1

Table 7-26 gives an overview of the main assumptions made to assess the international transport costs in the form of ammonia (NH_3) and liquid hydrogen (LH_2) for 2030.

Transport value chain	**Unit**	**NH_3**	**LH_2**
General Assumptions			
WACC for all investments	%	8	
Project duration	a	25	
Indirect cost header	%	30	
Electricity costs			
PoL	USD / MWh	80	
PoD	USD / MWh	100	
Conversion Assumptions			
Spec. direct cost	USD/TPAoutput	360	6,357
O&M	%	5	2
VLH	h/a	8,000	
H_2 consumption	t/tproduct	0.18	1
Electricity consumption	MWh/ tproduct	0.2	7.5
Export facility Assumptions			
Transport value chain	**Unit**	NH_3	LH_2

Storage sizing	-	Max (6,25% of throughput and biggest vessel + 8 days)	
Jetty	-	New building	
Direct Costs per Jetty	USD / Jetty	35 Mio.	
Port fees	USD / t	5.25	5
Boil-off	%/day	0,04	0,2
Boil-off handling	-	Reliquefication	Reliquefication
Power reliquefication	MWh/texport	0.2	10
Power vessel loading	MWh/t	0.01	0.01
Spec. direct cost	USD/tstorage	1,316	87,616
O&M	%	4	1.5
Shipping Assumptions			
Density	t/m³	0.68	0.0708
Shipping model	-	Chartered	
Bunker fuel	-	NH_3	

Transport value chain	**Unit**	**NH_3**	**LH_2**
Bunker fuel costs	USD / t	850	
Fuel consumption:			
Laden	tHFO / day	35	81

Ballast	tHFO / day	33	75
Port	tHFO / day	6	5
Boil off handling	-	Used as bunker fuel	Used as bunker fuel
Boil-off	%/day	0.04	0.2
Product insurances	-	Excl.	
Vessel type	-	LGC	LH_2 large
Daily time charter rate	USD / day	29,000	152,417
Ballast share	%	100	100
Canal fees	USD	Excl.	Excl.
Import facility Assumptions			
Storage sizing	-	Max (6,25% of throughput and biggest vessel + 8 days)	
Jetty	-	New building	
Transport value chain	**Unit**	**NH_3**	**LH_2**
Direct Costs per Jetty	USD / Jetty	35 Mio.	
Port fees	USD / t	5.25	5
Boil-off handling	-	Reliquefication	Reliquefication
Power reliquefication	MWh/t	0.2	10
Power Export	MWh/texport	0.01	0.01
Spec. direct cost	USD/tstorage	1,324	105,110
O&M	%	4	1.5

Reconversion Assumptions			
Spec. direct cost	USD/TPAout	2,400	515
O&M	%	5	2.5
VLH	h/a	8,500	
Thermal power supply	-	By transport chain	
Losses	%	22	0
Electricity consumption	MWh / tproduct	0.173	0.1

Table 7-26: Overview of main assumptions for international transport cost calculation

For the 2040 scenario CAPEX cost reduction in the order of 50% have been applied for:

- Hydrogen liquefaction plant
- LH_2 vessel costs
- LH_2 storage costs
- NH_3 cracking costs

Furthermore, the NH_3 cracking efficiency has been increased by 2% and the liquefaction power consumption decreased by 5%. These cost reduction and efficiency increases are based on the complete novelty of the technologies for projects in 2030 and significant learning rates foreseen based on the first execution of export projects. Further changes with significant impact (e.g. reduction of power prices for synthesis plants, reduction in WACC, increase in vessel sizes due to new ports) have not been applied, since the development cannot be passed by the author.

List of Abbreviations

Appr.	approximately
AACE	Association for Advancement of Cost Engineering International
CAPEX	Capital expenditures
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
BFD	Block Flow Diagram
EAEU	Eurasian Economic Union
EHB	European Hydrogen Backbone
EU	European Union
GDP	Gross Domestic Product
GIZ	Deutsche Gesellschaft für internationale Zusammenarbeit (GIZ) GmbH
LCOA	Landed costs of ammonia
LCOH	Landed costs of hydrogen
LCOT	Levelized costs of transport
OPEX	Operational expenses
PtX	Power-to-X
RE	Renewable energy
RoRo	Roll-on-Roll-off
SCP	South Caucasus Pipeline
SGC	Southern Gas Corridor
ToR	Terms of Reference
TSO	Transmission System Operator
WACC	Weighted Average Costs of Capital

Elements and Compounds

H_2	Hydrogen
LH_2	Liquefied hydrogen
NH_3	Ammonia
CO_2	Carbon dioxide

Units

a	Annum
bcm	Billion cubic meters
EUR	Euros (€)
h	hour
kg	Kilogramm
km	Kilometers
Mln	Million (1,000,000)
mm	millimeters
MW	Megawatt
Mtpa	Mega tons per annum
TEU	Twenty-foot equivalent unit
t	Tonne(s)
tkm	Tonne-kilometre
USD	United States Dollars ($)