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Decentralized use case integration of chemical hydrogen carriers: The cost saving potential in domestic supply chains

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A R T I C L E I N F O

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A B S T R A C T

The use of chemical hydrogen carriers such as ammonia (NH_3), methanol (MeOH), dimethyl ether (DME), and liquid organic hydrogen carriers (LOHC) is considered as a potential option for hydrogen imports. Following import, the carriers are either converted centrally into hydrogen or transported further to the point of use. This study evaluates various domestic transport options – truck, rail, inland waterway, and pipeline – as unimodal or intermodal transport for hydrogen and chemical hydrogen carriers. Based on this, the potential of transport and decentralized integration of carriers for various locations is assessed. A cost comparison is used to determine the maximum specific costs that a decentralized conversion plant can incur while remaining competitive with a centralized conversion plant in the port. The analysis shows that the specific costs of decentralized conversion plants at numerous locations can be significantly higher than those of centralized plants, indicating considerable cost-saving potential.

Nomenclature

Abbreviation	Description
AF	Annuity factor
ATR	Autothermal reforming
BP	Boiling point
BT	Benzyltoluene
CAPEX	Capital expenditure
CCUS	Carbon capture, utilization and storage
CGH_2	Compressed gaseous hydrogen
CO_2	Carbon dioxide
DBT	Dibenzyltoluene
DME	Dimethyl ether
LHV	Lower heating value
LH_2	Liquid hydrogen
LPG	Liquid petroleum gas
LOHC	Liquid organic hydrogen carrier
MeOH	Methanol
MP	Melting point
NH_3	Ammonia
OPEX	Operational expenditures
PSA	Pressure swing adsorption
SMR	Steam methane reforming
TRL	Technology readiness level
WACC	Weighted average cost of capital

1. Introduction

Many national hydrogen strategies haven been published [1], and the use of hydrogen is planned in many applications. Ensuring the supply of hydrogen for all future applications is of great importance for its successful implementation. On the one hand, hydrogen must be available and, on the other hand, it must be possible to supply it to the point of use in an economically attractive manner. However, the amount of hydrogen produces locally in Central Europe will not be sufficient, and the production of green hydrogen is more economical feasible in countries with abundant solar and wind energy [2,3]. Therefore, a need of import is given, and a global trade is expected.

There are various options for importing hydrogen, each with different advantages and disadvantages. Pipelines for compressed gaseous hydrogen (CGH_2) are the most efficient method of transport [4] and the most cost-effective supply option [5,6] up to a certain distance [7,8]. But pipelines require substantial infrastructure, and geopolitical risks at multiple border crossings have a significant impact on the their bankability [9]. Furthermore, there is a hard to solve chicken-egg problem between market and demand. A more flexible and

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risk-distributed supply pathway is maritime import of liquified hydrogen (LH_2) or chemical hydrogen carriers [9]. LH_2 has a higher energy density than CGH_2 allowing respective ships to transport large quantities of hydrogen. Feasibility has already been demonstrated [10], but LH_2 ships still have a low technology readiness level (TRL) [4]. Large scale imports of LH_2 are not realistic in the near future, as significant scaling and completely new infrastructure for storage, loading, and unloading are required [7]. Chemical hydrogen carriers such as ammonia (NH_3), methanol (MeOH), dimethyl ether (DME) or liquid organic hydrogen carriers (LOHC) chemically bind hydrogen to carrier molecules and are easier to transport than neat hydrogen. These carriers can be synthetized after hydrogen production in the exporting country and then transported in large quantities by ship to the importing countries. Many of the carriers mentioned are chemicals that are widely used in other sectors and are therefore already traded worldwide today. Much of the infrastructure already exists and the transport options have a high TRL [4]. Large-scale imports of chemical carriers are necessary for the market ramp-up and can be realized in the near future. Import routes and carriers have been investigated intensively in the past [6, 11–14].

Depending on the infrastructure in the importing country and the application, different scenarios can arise for the location of the reconversion of the carrier. In most import concepts or published plans, the chemical hydrogen carrier gets converted back into the carrier molecule and hydrogen centralized at the port [15–17]. The hydrogen is then fed into a pipeline network. As for international transport, hydrogen pipeline are the cheapest and most efficient transport option [18]. Most of the hydrogen demand in Germany will be covered by the hydrogen core network pipeline [19]. However, small and medium-sized companies are often located in remote areas and will not have their own pipeline connection. This leaves a hydrogen demand that is not covered by the core network [19]. The question arises as to how energy-intensive application located in remote areas without own pipeline connection, can be supplied with hydrogen or the energy needed.

Alternative transport options for CGH_2 to the pipeline are truck, rail, and ship transport, which can get very expensive [18,20]. In addition, hydrogen can be liquefied and transported as LH_2, but liquefaction also leads to high costs. Transporting chemical hydrogen carriers, on the other hand, is far more feasible because the transport conditions are more manageable. NH_3 and DME can be liquefied at moderate temperatures or pressures and MeOH and LOHC are liquid at ambient conditions (see Table 1). The transport is more cost-effective and the suitable infrastructure is already in place [6]. From a transport perspective, transporting chemical hydrogen carriers is preferable to transporting hydrogen (excluding pipelines). However, conversion must then take place locally in a decentralized manner. Small-scale, decentralized plants initially result in higher specific costs than large-scale centralized plants but also offer greater flexibility. Centralized plants are designed for the specifications of the pipeline (high pressure and high purity requirements), while decentralized plant designs can be tailored to the individual application. Depending on the application, this can lead to cost savings and additional expenses.

The transport of hydrogen has already been examined in many studies, whereby the majority focus on import and international transport. [5,6,11–13]. Domestic supply chains, on the other hand, are rarely considered or are greatly simplified by not taking all transport options into account [20–23]. Scheffler et al. [24], for example, examined import routes in great detail and considered various carriers, but then only considered hydrogen pipelines for domestic transport. Rapp et al. [25] examined domestic transport in more detail and compared different modes of transport for CGH_2 and LH_2. However, hydrogen carriers were not examined for domestic transport. Eiβler et al. [26] also identified domestic transport as a gap in the literature and examined domestic transport for LH_2, MeOH, and NH_3 using different modes of transport. However, they did not consider intermodal transport and did not include LOHC and DME in the carrier selection. Spillmann et al. [27] conducted a comprehensive study on the distribution options for hydrogen within the country, examining many transport options. However, the study did not consider LOHC and DME as possible carriers, and decentralized conversions of hydrogen carriers were not discussed. Further studies are needed that cover all domestic transport modes and include the full range of commodities rather than focus on individual ones. This will make it possible to examine the domestic hydrogen supply in more detail and identify the most cost-effective supply option. However, as decentralized conversion plants are still at a very early stage of development, they remain the missing link in the supply chain and in the comparison of hydrogen supply options. It is therefore important to evaluate the cost-saving potential of decentralized solutions involving the transport of hydrogen carriers in order to determine whether further development is worthwhile and should be pursued.

To address the outlined problem, we developed a method to calculate the cost of domestic hydrogen supply at various locations and to determine the maximum allowable specific cost of decentralized conversion units. The costs of supplying hydrogen include conversion at the port, conditioning, and transport of pure hydrogen. The supply of the carrier only includes its transport. As a result, the comparison of costs leads to the maximum allowable specific costs at which decentralized plants remain economically feasible compared to the transport of neat hydrogen. Based on these marginal cost thresholds, the integration potential of decentralized use cases can be assessed. We applied this approach to compare transport costs in a specific scenario and to evaluate the feasibility of decentralized conversion. Our method supports informed decisions on where decentralized solutions are practical and should be further pursued. Additionally, it provides guidance for the development of infrastructure and supply logistics for green energy systems.

2. Method

We built our model in Python based on calculations methods and assumptions from the literature. All assumptions are listed and explained in the following sections, while the calculation methods and

Table 1
Comparison of chemical hydrogen carrier properties.

Carrier	MP [°C]	BP [°C]	H_2-Capacity [wt%]	Gravimetric Energy Density [kWh/kg]	Density [kg/m^3]	Transport state
CGH_2	−259	−253	100	33.3	40 (500 bar)	Gaseous (Pipeline: 80 bar, Truck: 500 bar)
LH_2	−259	−253	100	33.3	70	Liquid @ −253 °C
NH_3	−78	−33	17.8	5.3	680	Liquid @ 10 bar (for small-scale storage) Liquid @ −34 °C (for large-scale storage)
MeOH	−98	64	12.5/18.8[a]	5.6	790	Liquid at ambient conditions
DME	−116	−24	13.0/26.1[a]	8.0	680	Liquid @ 6 bar (for small-scale storage) Liquid @ −25 °C (for large-scale storage)
LOHC: H0-BT/H12-BT	−80 - - 70/-70	285/280	6.2	2.2 (H_2)	995/876–996	Liquid at ambient conditions

[a] Pure material/technical (with additional hydrogen from reforming reaction).

uncertainties of the assumptions are listed in the appendix.

The starting point of all our supply chains is the port, where the chemical hydrogen carriers are imported (NH_3, MeOH, DME, LOHC). The destination is an energy-intensive application, which requires hydrogen. Three categories of domestic supply chains are possible to supply this hydrogen – 1. Conv-CGH_2, 2. Conv-LH_2 and 3. Carrier (see Fig. 1). In the first two categories, the carrier is converted back into hydrogen in a large-scale centralized conversion plant (Conv) at the port. The hydrogen is then either compressed and transported as CGH_2 (Conv-CGH_2) or liquefied and transported as LH_2 (Conv-LH_2). The third category involves transporting the carrier to the point of use with subsequent decentralized conversion (Carrier). For all carriers and hydrogen, we considered transport by truck, rail and ship, either unimodal or intermodal, and additionally a pipeline for the transport of CGH_2.

The aim of this study is to evaluate the potential of the third category - carrier transport and decentralized conversion (Carrier) – compared to the other two categories involving centralized conversion and hydrogen transport (Conv-CGH_2 and Conv-LH_2). Decentralized systems can vary depending on the application and require individual assessment for each specific use case. Development is still at a very early stage, so an investigation is needed to determine whether further development is worthwhile or not.

To assess the potential, our model calculates the maximum specific costs that a decentralized plant may incur to compete with the first two categories (hydrogen transport). If the maximum allowable specific costs are low, transporting the carrier offers few advantages and delivering hydrogen with prior centralized conversion is preferable. If the maximum specific costs are high, there is potential for cost reduction via decentralized conversion and it should be evaluated to transport the carrier beyond the port and integrate the reconversion into the use case.

The transport costs depend heavily on distances, and the possible domestic supply chains depend on the connection options at the application site (own pipeline connection, port or rail connection). Therefore, the model requires a defined scenario for which the domestic supply costs and the maximum allowable specific costs can then be calculated. The parameters that define a scenario are the location of the import port and the application (or the distances of the modes of transport), the local connection options, and the pipeline utilization. This study focuses on applications in remote areas, as decentralized systems are most likely to be considered there. We assume that the last mile must always be covered by truck and that the application does not have its own pipeline connection, port, or rail connection.

First the model calculates the costs for all possible domestic supply chains with centralized conversion (Conv-CGH_2 and Conv-LH_2) and the most cost-effective gets determined as a benchmark. Then, all possible transport options for the carrier under consideration are calculated, and the most cost-effective one is determined again. The cost difference between these two cost-optimal supply chains yields the desired marginal costs of the decentralized plants. All calculated costs for the individual steps of the supply chains in this study refer to marginal costs, meaning that no profits are taken into account.

2.1. Supply chains and cost calculation

The model follows a modular approach, so that each part of the supply chain (e.g. conversion, compression, truck transport) is considered as an independent unit, resulting in specific costs in €/kg_{H2}. These units can be combined into supply chains, and the costs are added up. Any losses in mass and energy incurred are charged directly to the costs of the respective unit to ensure their independence. The import costs of the carriers are not included in the costs, as this study focuses on domestic supply. The aim is not to compare the total costs of different carriers with each other, but to compare the different supply chain configurations (with centralized vs. with decentralized conversion) for one given carrier. In this comparison, the import costs are the same for both configurations and therefore do not have to be considered in this analysis. In addition, the import prices of future green chemical hydrogen carriers are not yet available and can only be estimated with a high degree of uncertainty. The costs calculated in this study are therefore not total costs, but domestic supply costs between the port and the point of use. They are calculated individually for each carrier.

There are three types of units: conversion (conv), conditioning (cond), and transport (trans). Conversion refers to the centralized conversion plant at the port. Conditioning includes either compression or liquefaction. Transport can be by pipeline (only for CGH_2), truck, rail, ship, or, in the case of intermodal transport, a combination of these. For each carrier analyzed, all supply chains from the three categories "Conv-CGH_2", "Conv-LH_2" and "Carrier" (see Fig. 1) are formed. The respective number of possible combinations H, K, or J for the three categories depend on the scenario and the connections options of the application. In the first step, the costs of all supply chains are calculated.

$$C_{Conv-CGH2,h} = C_{conv,h} + \sum C_{cond,h} + \sum C_{trans,h}, \forall h \in H \tag{2.1}$$

$$C_{Conv-LH2,k} = C_{conv,k} + \sum C_{cond,k} + \sum C_{trans,k}, \forall k \in K \tag{2.2}$$

$$C_{Carrier,j} = \sum C_{trans,j}, \forall j \in J \tag{2.3}$$

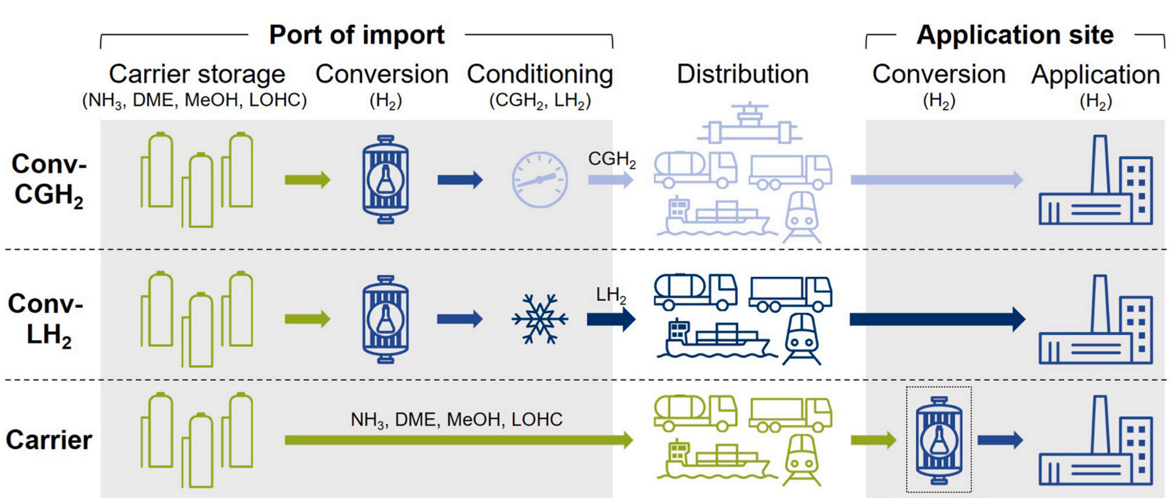

Fig. 1. – Categories of domestic supply chain options from the port of import to an application requiring hydrogen.

Next, the most cost-effective supply chains with centralized reconversion and decentralized reconversion are determined from the previously calculated sets.

$$C^{min}_{centralized} = \min_{h \in H, k \in K}\left(C_{Conv-CGH2,h}, C_{Conv-LH2,k}\right) \quad 2.4$$

$$C^{min}_{decentralized} = \min_{j \in J}\left(C_{Carrier,j}\right) \quad 2.5$$

Allowable specific costs $C_{allowable}$ are the cost difference between the most cost-effective supply chain with centralized reconversion (Conv-CGH_2 and Conv-LH_2) and with decentralized reconversion (Carrier). They describe the maximum costs that decentralized conversion plants may incur to remain economically competitive with the centralized conversion at the port and the transport of pure hydrogen.

$$C_{allowable} = C^{min}_{centralized} - C^{min}_{decentralized} \quad 2.6$$

2.1.1. Uncertainties and error bars

All calculations are based on assumptions listed in the following tables. We have specified a range for many values in the appendix to increase the robustness of the results. Where literature data was available, other references were used to determine the range. Where no reliable literature data was available, we determined the uncertainties based on the cost estimate classes of AACE international [28]. The uncertainties and the range were used to calculate the error bars for all costs. All best-case assumptions result in the lowest costs of a supply chain, and all worst-case assumptions result in the highest costs, which are both shown in the error bars of the results.

2.2. Conversion and conditioning processes

The conversion costs and conditioning costs were calculated using the annuity method. The annuity factor (AF_i) is calculated based on the weighted averaged capital costs (wacc) and the lifetime of the plant n_i for each unit of a supply chain i.

$$AF_i = \frac{wacc*(1+wacc)^{n_i}}{(1+wacc)^{n_i}-1} \quad 2.7$$

The investment costs (Capex) are given for a reference plant with a reference size $S_{i,base}$. All centralized plants in the port are assumed to have a size of 500 t_{H2}/d. Therefore, the Capex are scaled up to the required size with a scaling factor α.

$$Capex_i = Capex_{i,base}*\left(\frac{S_i}{S_{i,base}}\right)^{\alpha} \quad 2.8$$

Not every plant can be scaled directly to 500 t_{H2}/d, as the process cannot be implemented on such a large scale. In this case, we have assumed a numbering up of the largest possible plant for the respective process. First, the largest possible divisor of the plant and the target value (500 t_{H2}/d) is formed. The costs of the reference plant are then scaled up to this plant size using the scaling factor alpha. After that, the costs are scaled linearly, which is like numbering up the plant to the target plant size at the port.

The costs of the unit are calculated using the scaled capital costs, the operating costs (Opex), and the annual amount of hydrogen filled. The annual amount of hydrogen filled is the annual amount of hydrogen produced (for the given plant size S_i) minus losses. These mainly result from purification or leaks. For conditioning plants, the annual operating costs consist of fixed costs and electricity costs. Conversion plants also have a heat requirement that must be met. We assume that centralized plants cover this with hydrogen, which is why the hydrogen required for heat supply in the case of conversion plants is also included in the losses.

$$m_{H2,fill} = m_{H2,prod} - m_{H2,losses} \quad 2.9$$

$$C_{conversion}, C_{conditioning} = \frac{Capex_i*AF_i + OPEX_i}{m_{H2,fill}*Availability_i} \quad 2.10$$

The general assumptions for plants are listed in Table 2, unless otherwise specified in one of the following tables.

2.2.1. Conversion plants

Ammonia is converted back into hydrogen and nitrogen in so-called ammonia crackers according to Equation (2.11). The reaction takes place preferentially at high temperatures and low pressures.

$$2NH_3 \leftrightarrow 3H_2 + N_2, \quad 2.11$$

The ammonia cracker in this study is based on a Steam Methane Reformer (SMR) like plant design as a reference. SMR's are a proven technology, and large-scale plants are currently being built based on this concept [33]. A cost-effective nickel catalyst can be used, and the reactor operates at high temperatures of up to 900 °C and pressures of up to 40 bars to reduce subsequent compression. The planned KBR plant in Korea with a hydrogen output of 200 t_{H2}/d [34,35] was used as the main reference. Pressure swing adsorption (PSA) is used for purification.

Methanol is converted into carbon dioxide and hydrogen according to Equation (2.12) when water is used as oxidizing agent. In this case, the water also increases the hydrogen yield, as the water releases an additional hydrogen molecule.

$$CH_3OH + H_2O \leftrightarrow CO_2 + 3H_2 \quad 2.12$$

Various process concepts are possible for MeOH reforming. Commercially available reformer uses low-temperature reforming at temperatures of 250–300 °C. However, the scalability of these reformers to large-scale plants is questionable. Steam reformers or autothermal reformers (ATR), on the other hand, are feasible for large-scale reforming. In any case, a carbon capture unit is needed to avoid CO_2-emissions and recapture the carrier molecule. In this study, several assumptions were made to calculate the costs of a large-scale MeOH reformer. The investment costs are based on a SMR plant with CCS as a conservative estimate by Oni et al. with a base capacity of 600 t_{H2}/d [36]. The conversion rate was taken from small-scale plants that are already in operation today – also as a conservative estimate [37]. The losses incurred are negative for the MeOH reformer, as additional hydrogen is released by the water during steam reforming (see Eq. (2.12)). Purification is again carried out by a PSA.

The reforming reaction of dimethyl ether is shown in Equation (2.13). As with methanol, water acts as an oxidizing agent, which again increases the hydrogen yield. During DME reforming, three additional hydrogen molecules are released by the water.

$$CH_3OCH_3 + 3H_2O \leftrightarrow 2CO_2 + 6H_2 \quad 2.13$$

The SMR plant with CCS from Oni et al. is also used as a conservative estimate for large-scale DME conversion plants [36]. The electricity demand and the conversion rate are taken from Ruther et al. [38], with an additional electricity demand for the separation and conditioning of the CO_2 [39].The negative losses are slightly higher for DME than for MeOH [40]. As with ammonia cracker and methanol reformer, a PSA is used for purification.

LOHC is a general term for various substances, the two most commonly discussed being benzyltoluene-perhydrobenzyltoluene (BT) and toluene-methylcyclohexane (TOL). In this study, we use BT as LOHC, as leading licensors such as Hydrogenious LOHC Technologies

Table 2
General techno-economic assumptions of conditioning and conversion units.

Parameter	Unit	Value
Availability	h/a	8000 [29–31]
Wacc	%/a	8 [24]
Electricity price	€/kWh	0.15 [32]

Table 3
Techno-economic assumptions of centralized conversion plants.

Parameter	Unit	NH_3	MeOH	DME	LOHC
Base Capex	k€ (k€/tpdH2)	125,800 (629)[a,b,] [34]	611,856 (1008)[a,] [36]	611,856 (1008)[a,] [36]	60,120 (501) [24]
Base capacity	t_{H2}/d	200 [34]	607 [36]	607 [36]	120 [24]
Max. capacity per train	t_{H2}/d	1200 [34]	700	700	250 [24]
Fix. Opex	$\%_{Capex}/a$	4 [5]	4 [5]	4	4 [5]
Scaling factor α	–	0.85 [20]	0.74 [41]	0.74	0.6 [24]
Lifetime	a	20 [27]	20 [20]	20	20 [42]
Electricity demand	kWh/kg_{H2}	0.1 [35]	1.23	1.23 [38,39]	0.37 [24]
Conversion rate	$kg_{Carrier}/kg_{H2}$	7.21 [35]	6.89 [24]	5.88 [38]	24.33 [43]
H_2-Losses	–	0.22 [35]	−0.15 [24]	−0.31 [38]	0.34 [43]
Output pressure	bar	40 [35]	27	27 [38]	2 [24]

[a] Value converted from $ to € using the DAC conversion rate for the year of publication [44].
[b] Capex calculated with an assumed annuity factor of 0.10185.

are currently demonstrating large-scale projects with BT. Nevertheless, the characteristics relevant to this study differ only slightly between the carrier materials, which is why the statements on LOHC can be interpreted in general terms. During dehydrogenation, the hydrogen-loaded LOHC (H12-BT) releases the bound hydrogen (see Eq. (2.14)). The resulting unloaded LOHC (H0-BT) is then transported back to the hydrogenation process, where it can be reloaded with hydrogen.

$$H12\text{-}BT \leftrightarrow H0\text{-}BT + 6\,H_2 \qquad 2.14$$

For large-scale dehydrogenation, a reference plant design was used by Scheffler et al. [24]. The reference size is 120 t_{H2}/d and the output pressure 2 bar. No purification unit is required, but high losses occur to provide the heat needed for dehydrogenation.

No separate costs were calculated for decentralized conversion plants after transport of the carrier. Decentralized plants are still in a very early stage of development, and their design is highly dependent on the specific application. Instead of calculating costs based on assumed data, as is the case for the other units, the costs of decentralized plants will be calculated by the model at a later stage. The costs calculated by the model are the maximum allowable specific costs for decentralized solutions to be economically competitive with centralized conversion and subsequent transport of hydrogen. Therefore, no data is available for decentralized plants; instead, the costs of these plants are the target value of the model. All assumptions for the centralized conversion plants are listed in Table 3.

2.2.2. Compressor

CGH_2 requires compression after centralized conversion at the port for transport. The pipeline operates at a pressure of 80 bar and the other transportation methods (tube trailers or containers) use 500 bar. For the large-scale compressors downstream of the centralized conversion plants, a plant size of 500 t_{H2}/d is again assumed. The largest compressors today are in the order of 216 t_{H2}/d [45]. Accordingly, we first scaled up and then numbered up the process (see Section 2.1). For large-scale compressors at the port, this results in three 167 t_{H2}/d compressors. If hydrogen is first transported by pipeline and then by truck for the last mile, a second compressor is required after the pipeline. This study assumes hydrogen hubs where the pipeline hydrogen is further compressed to 500 bar and transferred to tube trailers. The size of these compressors was set to 7.2 t_{H2}/d [46]. We assumed a multi-stage piston compressor with intercooling and a constant pressure ratio per stage. The electrical power is calculated for the inlet pressure p_{in}, the outlet pressure p_{out} and the flow rate [47]. A detailed calculation is given in the appendix. The investment costs are calculated based on electrical power consumption, the installation factor IF = 2 and indirect costs IC = 0.4 [48]. Losses may occur due to leakages.

$$Capex_{Compressor} = 2759.4 * P^{0.8225} * IF * (1 + IC) \qquad 2.15$$

2.2.3. Liquefier

LH_2 enables the transport of neat hydrogen with a higher volumetric energy density than CGH_2. To achieve this, the hydrogen is liquefied in the port after conversion of the carrier instead of being compressed. In the future, it might also be possible to import LH_2 directly, which would eliminate the need for liquefaction at the port. This could potentially lead to a substantial reduction in the costs of a LH_2-based supply chain. As large-scale import of LH_2 does not appear to be feasible within the forthcoming years, it was not considered in this study. This paper uses a Claude cycle with mixed refrigerant (MR) as a reference plant and a electricity demand of 6.7 kWh/kg_{H2} [49,50]. Although the power requirement of today's plants is around 11 kWh/kg_{H2}, several studies assume lower power requirements for large-scale plants [7,50,51]. Losses again can occur due to leakages and boil off during storing and filling. The assumptions for the liquefier and compressor are listed together in Table 4.

2.3. Transport options

Both unimodal (only one mode of transport) and intermodal transport (combination of at least two modes of transport) are considered as inland transport options. For unimodal truck and rail transport, bulk transport is assumed for chemical hydrogen carriers, while container-

Table 4
Techno-economic assumptions of conditioning units.

Parameter	Unit	Compressor at the port	Compressor at the pipeline	Liquefier
Base Capex	k€ (k€/tpdH2)			134,000 (2,680) [50]
Base capacity	t_{H2}/d	–	–	50 [50]
Max. capacity per train	t_{H2}/d	216 [45]	216 [45]	200 [52]
Fix. Opex	$\%_{Capex}/a$	5.4 [47]	5.4 [47]	4 [20]
Alpha	–	–	–	0.66 [53]
Lifetime	a	15 [54]	15 [54]	30 [20]
Electricity demand	kWh/kg_{H2}	Calc.	Calc.	6.76 [53]
H_2-Losses	%	0.9[a]	0.9[a]	1.65 [55]
Input pressure	bar	Depending on the conversion	80	/
Output pressure	bar	80	500	2 [55]

[a] Based on expert interview (literature data: 0.5 [24,46]).

based options are assumed for intermodal transport and unimodal ship transport. LH_2 is transported in optimized trailers for unimodal truck transport and in containers for all other modes of transport (unimodal railway and ship transport and intermodal transport). CGH_2 is always transported in containers.

We assumed that the investment costs are not borne by the company of the hydrogen application but by freight forwarder. We also assume that the freight forwarder will always operate at full capacity. This is a best-case scenario, but a freight forwarder will try to achieve this to minimize costs and thus maximize profits. The investment costs are distributed over the annual costs using the AF, as described for the conversion and conditioning plants (see Eq. (2.7)). The distances are determined depending on the scenario selected or the locations of the port and the industrial site. More details are provided in the appendix for all modes of transport.

2.3.1. Truck

The speed was set at 60 km/h, fuel consumption at 0.35 l/km, fuel costs at 1.6 €/l, driver labour costs at 35 €/h, and utilization at 4818 h/year. In Germany, there is a driving ban on Sundays and public holidays [56], and night driving was also avoided. The transport pressure for CGH_2 trailer and container was 500 bar.

The transport of LH_2 results in losses that occur during the filling process. In this study, the losses are calculated with a scaled daily boil-off rate to simplify the calculation. All other assumptions are listed in Table 5.

2.3.2. Railway

Unimodal rail transport is possible if the customer has its own rail connection. In this case, the chemical hydrogen carriers can be transported in tank wagons with very large capacities (see Table 6). Neat hydrogen cannot benefit from this, as complicated transport conditions do not allow for large transport volumes. For LGH_2 and CGH_2, we have assumed rail transport by container, the costs of which correspond to those of transport by truck. However, LH_2 containers are slightly smaller than LH_2 trucks. If there is no dedicated rail connection, the last mile must be covered by truck, resulting in intermodal transport. The speed of the train was set at 45 km/h, the number of wagons per train at 30 wagons/train, and the utilization at 8760 h/year [23,52]. Freight costs were based on a report published by Panteia in 2023 [63], which listed the total annual costs for various means of transport. For rail transport, we used the average of the two modes "wagon load" and "shuttle" which results in costs of 5.4 m€/year. The costs were converted into specific costs per wagon for the distance considered. More detailed information can be found in the appendix. Unlike trucks, rail transport in Germany is not subject to driving bans on Sundays and public holidays. We assumed that the tank wagons are already filled, so that the filling process is not included in the loading time.

2.3.3. Ship

For both hydrogen and chemical hydrogen carrier, shipping will always be covered by containers. Although bulk transport by inland waterway is also conceivable for carriers [65], this study focuses on applications in remote areas with lower hydrogen demands, where transport in containers is more suitable [66]. The speed of the ship is set at 16 km/h, the number of container per ship at 100 container/ship, the loading and unloading time at 16 h/trip, and the utilization at 8760 h/year (as for rail transport) [25]. The freight costs are again taken from the Panteia report as total annual costs (around 934 k€/year) [63] and converted into costs per container. All other assumptions are given in Table 7.

2.3.4. Intermodal

Intermodal transport describes the combination of several modes of transport. Hydrogen carriers or conditioned hydrogen are transported in containers that can be quickly transferred from one mode of transport to another. This reduces transfer times and costs. Intermodal transport already plays a very important role in the transport sector today and will be expanded increasingly in the future. Combinations of trucks, ships, and trains are possible. We have assumed 91 €/Container for the transfer costs at the port and 47 €/Container for the transfer at the rail terminal [67,68]. The assumptions for container transport are listed in Table 7.

2.3.5. Pipeline

Even though the study focuses on applications without a pipeline connection on site, a combination of pipeline and truck for the last mile may be useful. The costs are calculated based on the costs for the hydrogen backbone for three different diameters, new- and retrofitted pipelines and different utilizations [69,70]. A detailed breakdown of the cost calculation is given in the Appendix. At 100 % utilization, the costs amount to 0.227 €/kg_{H2}/1000 km and at 25 % utilization to 0.496 €/kg_{H2}/1000 km. The costs for all other utilization rates are calculated by linear interpolation between these values.

3. Results

The costs of supply between the port and the point of use were calculated for a defined scenario with specified distances and pipeline utilization. The calculation is based on a modular approach in which all individual components of the domestic supply chain (centralized conversion, compression, ship transport, etc.) can be combined into different supply chains. First, all feasible supply chains in the three categories shown in Fig. 1 (Conv-CGH_2, Conv-LH_2, Carrier) are formed and their costs calculated. The most cost-effective supply with centralized conversion at the port and subsequent hydrogen transport (Conv-CGH_2 or Conv-LH_2) is identified and compared with the carrier's most cost-effective transport option to the application site. The cost difference corresponds to the maximum cost that decentralized conversion could incur, so that the transport of the carrier and the decentralized

Table 5
Techno-economic assumptions Truck Transport (unimodal, trailer).

Parameter	Unit	Truck	CGH_2 (500 bar)	LH_2	NH_3	MeOH	DME	LOHC
Capex	k€	140[b], [26,52,57]	900[b], [20,58–60]	800[b], [20,26,59]	230[a]	90[a]	200[a]	90[a]
Opex	%Capex/a	12 [58,61]	2 [20]	2 [20]	2 [20]	2 [20]	2	2 [20]
Lifetime	a	8 [58,61]	12 [20]	12 [20]	12 [20]	12 [20]	12 [20]	12 [20]
Capacity	$kg_{Carrier}$(kg_{H2-eq})		1,100 [23]	3,900[a]	23,000[a](4,094)	25,000[a](3,125[c]/4,700[d])	23,000[a](2,990[c]/6,003[d])	25,000[a](1,550)
Loading & unloading time	h/trip		1.5 [58]	5 [62]	1.5 [20]	1.5 [20]	1.5	1.5 [20]
H_2-Losses	%/d		0 [20]	0.5[a]	0 [20]	0 [20]	0	0 [20]

[a] Based on expert interview.
[b] Own assumption based on literature data range.
[c] Calculated using hydrogen storage capacity of pure material.
[d] Calculated using hydrogen storage capacity of pure material plus additional water from reforming process.

Table 6
Techno-economic assumptions of rail transport (unimodal, tank wagon).

Parameter	Unit	CGH_2	LH_2	NH_3	MeOH	DME	LOHC
Capex	k€	900[a]	800[a]	163 [52]	109 [52]	163	128 [52]
Opex	%Capex/a	2[a]	2 [26]	2 [26]	2 [26]	2 [61]	2 [61]
Lifetime	a	12[a]	12[a]	45 [64]	45	45	45
Capacity	$kg_{Carrier}$($kg_{H2\text{-}eq}$)	1,100 [25]	3,000 [26]	55,700 [52](9,915)	63,200 [52](7,900[b]/ 11,881[c])	55,700(7,241[b]/ 14,538[c])	63,200(3,893)
Loading & unloading time	h/trip	8 [25]	8 [25]	8	8	8	8
H_2-Losses	%/d	0	0.5[a]	0	0	0	0

[a] Container transport assumed, using truck transport costs/data.
[b] Calculated using hydrogen storage capacity of pure material.
[c] Calculated using hydrogen storage capacity of pure material plus additional water from reforming process.

Table 7
Techno-economic assumptions of intermodal transport and ship transport (container).

Parameter	Unit	Semi-trailer	CGH_2	LH_2	NH_3	MeOH	DME	LOHC
Capex	k€	60 [52]	840[a]	740[a]	45	20	45	20
Opex	%Capex/a	2	2	2 [26]	2 [26]	2 [26]	2	2
Lifetime	a	12	12	12	12	12	12	12
Capacity	$kg_{Carrier}$($kg_{H2\text{-}eq}$)		1,100 [25]	3,000 [26]	23,000[b](4,094)	25,000[b](3,125[d] / 4,700[e])	23,000[b](2,990[d]/ 6,003[e])	25,000[b](1,550)
H_2-Losses	%/d		0	0.5[c]	0	0	0	0

[a] Derived from truck transport costs, excluding semi-trailer costs.
[b] Adapted to maximum truck payloads (see Truck Transport).
[c] Based on expert interview.
[d] Calculated using hydrogen storage capacity of pure material.
[e] Calculated using hydrogen storage capacity of pure material plus additional water from reforming process.

conversion is more economical than centralized conversion and transport of hydrogen. These costs help to evaluate the potential of decentralized conversion at the given location and for the given application. In addition, it can be assessed whether it is worthwhile to pursue further developments of decentralized use cases. Finally, the calculated allowable specific costs of decentralized conversion can be compared with the costs of centralized conversion.

In the scenario analyzed, Wilhelmshaven is the port of import, and the application is located at a remote location in Bavaria. The total distance is 800 km and the application has neither its own port nor a rail or pipeline connection. The last mile must be covered by truck in all cases and is 50 km for all transport options. The pipeline utilization is set at 75 %.

3.1. Transport costs

First, only the transport costs for the specified distances are discussed, excluding conversion processes and conditioning. The possible transport options for the scenario analyzed are 1. Pipeline and truck (Pip-Truck), 2. Truck only (Truck), 3. Rail and truck (Rail-Truck), 4. Ship

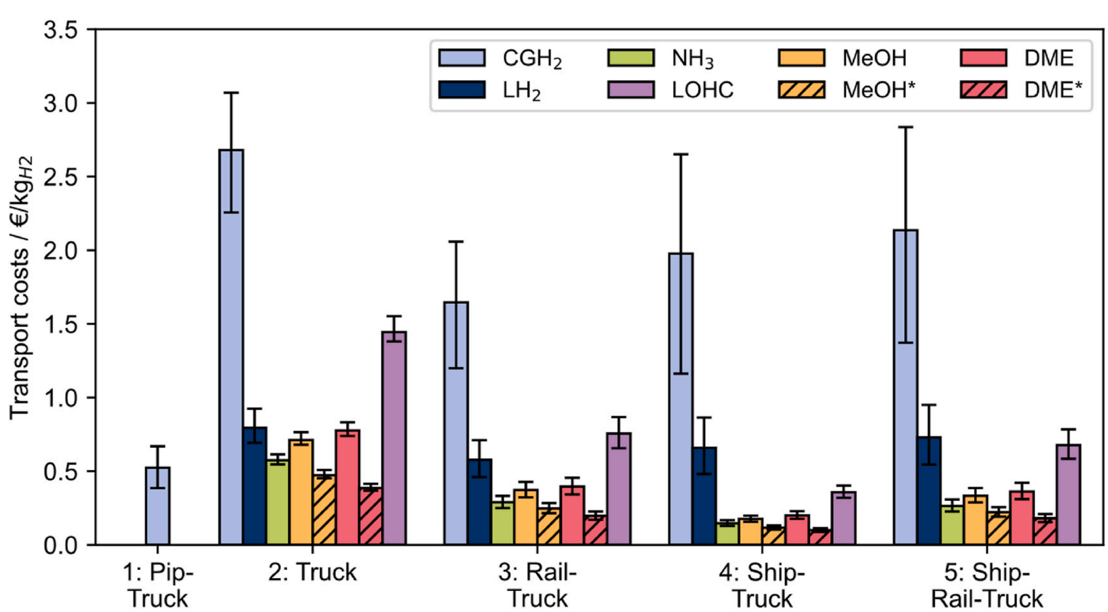

Fig. 2. – Transport costs for a distance of 800 km. The last mile is always covered by truck with a distance of 50 km for intermodal transport options (1,3,4,5). MeOH* and DME* use the higher hydrogen storage capacities (including hydrogen from the reforming reaction with water).

International Journal of Hydrogen Energy 186 (2025) 151928

and truck (Ship-Truck), 5. Ship, rail and truck (Ship-Rail-Truck) (Fig. 2). The first option (pipeline and truck) is only available for CGH_2, as a pipeline was only assumed for CGH_2.

Two different hydrogen storage densities can be used for MeOH and DME (see Table 1), depending on whether or not the additional hydrogen released by the water during steam reforming reaction is to be taken into account. The hatched bars are calculated using the higher storage density, which considers additional hydrogen from the steam. Based on this pseudo energy density/hydrogen capacity, more hydrogen can be transported per delivery and the costs are lower.

For all chemical hydrogen carriers, as well as CGH_2 and LH_2, delivery by truck only (option 2: Truck) is the most expensive mode of transport. This is due to high operating expenses (fuel costs, personnel costs, etc.). The combination of ship and truck (option 4: Ship-Truck) results in the lowest costs for chemical hydrogen carriers, even though ship transport involves long loading and unloading times. This is due to the low freight costs incurred by ships, because of the high number of containers they can transport. Rail and truck (option 3: Rail-Truck) and ship, rail and truck (option 5: Ship-Rail-Truck) are relatively similar for chemical hydrogen carriers. Transport by rail is more expensive than transport by ship, and transport costs are correspondingly higher when rail transport is included. For CGH_2 and LH_2, intermodal transport by truck and rail is less expensive than the combination of truck and ship.

Compared to the chemical hydrogen carriers and LH_2, CGH_2 always incurs the highest costs. Truck transport (option 2: Truck) of CGH_2 is particularly expensive, but the other transport options also remain costly. At 500 bar, CGH_2 is stored in small storage tanks housed in a container. This means that transport capacities remain low – 1,100 kg_{H2} in a CGH_2 trailer compared to an LH_2 trailer with a capacity of 3,900 kg_{H2} and NH_3 trailer with around 4,100 kg_{H2}. In addition, the large number of storage tanks leads to very high acquisition costs. The same applies to containers for intermodal transport by rail or ship. Transport using a combination of pipeline and truck (option 1: Pip-Truck), on the other hand, results in low costs that can compete with the transport of carriers.

LH_2 is the significantly cheaper option for transporting neat hydrogen. Even though the acquisition costs are also very high today, the high transport volume leads to lower transport costs. While the costs of truck transport are comparable to the costs of carriers, intermodal transport of LH_2 is more expensive than carriers (except LOHC). This is because LH_2 containers have a lower capacity than LH_2 trailers, but the acquisition costs remain very high.

The transport conditions for chemical hydrogen carriers are significantly more moderate than those for CGH_2 and LH_2 (see Table 1), and the transport of carriers has been well established for a long time. MeOH and LOHC can be transported in liquid form under ambient conditions. However, methanol is classified as toxic and easily flammable. LOHC is classified in a low hazard class and is easy to handle (non-flammable). NH_3 and DME are also highly flammable gases and must be transported in pressurized containers. The initial costs of the trailers and containers are therefore higher than for MeOH and LOHC. In addition, NH_3 is highly toxic and hazardous to water. Nevertheless, the trailers and containers are mature technologies for all chemical hydrogen carriers, and the initial costs are significantly lower than for trailers and containers for CGH_2 and LH_2.

Ammonia results in the lowest transport costs when the hydrogen storage densities for MeOH and DME are used, which refer to the hydrogen actually stored in the carrier. In this case, ammonia has the highest hydrogen storage density (see Table 1 if only the hydrogen in molecule is considered) and the highest amount of hydrogen transported per delivery. The slightly higher acquisition costs for ammonia trailers and containers, which arise from the higher material requirements for ammonia transport, are offset. However, DME and MeOH also result in low transport costs. DME is even the most cost-effective option, assuming steam reforming and taking into account the additional water released in the process.

LOHC is the easiest to transport and has the lowest hazard rating. However, the hydrogen storage density is only 6.2 wt-%, which means that the capacity of trailers and containers is low (1,000 kg_{H2}). This makes the transport of hydrogen by LOHC more expensive than the transport via the other chemical hydrogen carriers.

3.2. Allowable specific costs

To determine the maximum allowable specific costs, not only the transport costs must be considered, but the total domestic supply costs. In the case of hydrogen delivery, it must first be released from the imported carrier at the port and then conditioned for transport. Both steps result in additional costs that are incurred when delivering neat hydrogen. The model forms all domestic supply chains for the possible transport options between the port and the application, depending on the connection options at the application site. This is followed by a calculation of the costs.

Table 8 lists all supply chains for the scenario under consideration. The last mile is always shown by truck, which is why delivery must be intermodal or unimodal by truck. The first nine supply chains contribute to the transport of hydrogen (either as CGH_2 or LH_2) after centralized conversion of the imported carrier at the port. The following four supply chains are the transport options for the imported carrier if it is not converted at the port but transported on to the application site.

The calculated domestic supply chain costs for NH_3 as carrier are shown in Fig. 3. The results for the other chemical hydrogen carriers (MeOH, DME and LOHC) are provided in the appendix. The transport costs are the same as in Fig. 2, but the costs for conversion and conditioning have now been added to the supply chains involving hydrogen transport.

The compression of hydrogen is significantly less expensive than the liquefaction of hydrogen, which offsets the cost advantage of LH_2 transport. The domestic supply costs for CGH_2 (except Conv-CGH2-Pip-Truck) and LH_2 are in the same range. However, if LH_2 is specifically

Table 8
Analyzed domestic supply chains for the given scenario.

Domestic supply chains	Centralized conversion	Condit-ioning	Distribution	Decentralized conversion
Conv-CGH_2-Pip-Truck	Yes	CGH_2	Pipeline (@80 bar) + Compression + Truck (@500 bar)	No
Conv-CGH_2-Truck	Yes	CGH_2	Truck	No
Conv-CGH_2-Rail-Truck	Yes	CGH_2	Railway + Truck	No
Conv-CGH_2-Ship-Truck	Yes	CGH_2	Ship + Truck	No
Conv-CGH_2-Ship-Rail-Truck	Yes	CGH_2	Ship + Railway + Truck	No
Conv-LH_2-Truck	Yes	LH_2	Truck	No
Conv-LH_2-Rail-Truck	Yes	LH_2	Railway + Truck	No
Conv-LH_2-Ship-Truck	Yes	LH_2	Ship + Truck	No
Conv-LH_2-Ship-Rail-Truck	Yes	LH_2	Ship + Railway + Truck	No
Carrier-Truck	No	–	Truck	Yes
Carrier-Rail-Truck	No	–	Railway + Truck	Yes
Carrier-Ship-Truck	No	–	Ship + Truck	Yes
Carrier-Ship-Rail-Truck	No	–	Ship + Railway + Truck	Yes

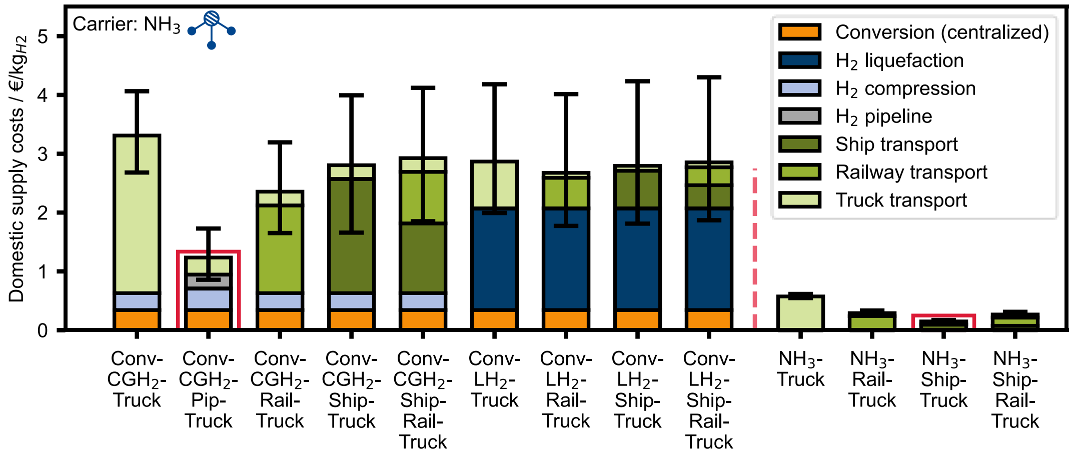

Fig. 3. – Domestic supply costs from port of import to the application with ammonia as chemical hydrogen carrier including conversion, conditioning and different transport options depending on the supply chain (distance = 800 km, last mile by truck = 50 km).

required for the application (e.g., for LH_2 filling stations) or LH_2 is imported at the port, LH_2-based supply chains may be a viable option. This is also in line with the findings of Sens et al. [20]. Supplying CGH_2 via pipeline and truck results in the lowest costs (Conv-CGH_2-Pip-Truck), as pipeline transport is the most cost-effective mode of transport (see Fig. 2). Although compression costs are slightly higher because a second compressor is required between the pipeline and the truck, these additional costs have no significant impact. The most expensive option is to transport CGH_2 by truck alone (Conv-CGH_2-Truck).

As already shown in Fig. 2, intermodal transport by ship and truck is the most cost-effective solution for NH_3 transport costs. The costs for decentralized conversion and conditioning plants are not calculated, as these costs are the target result of the analysis and will be calculated in the next step based on the cost difference between the cheapest supply

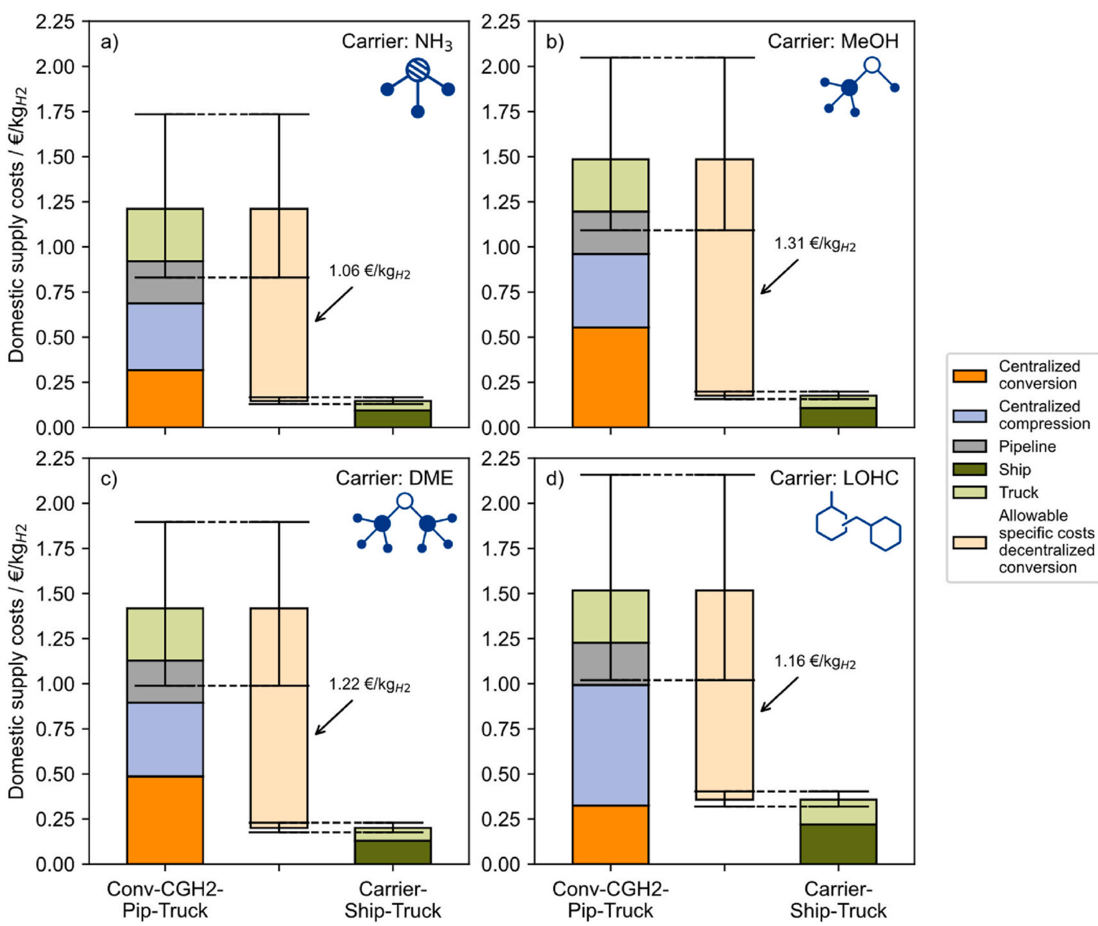

Fig. 4. – Comparison of the most cost-effective supply chain with centralized conversion at the port and subsequent hydrogen transport (left) with the most cost-effective carrier transport (right) to the point of application (distance = 800 km, last mile by truck = 50 km). The cost difference represents the allowable specific costs of decentralized conversion plants (center). a) NH_3, b) MeOH., c) DME, d) LOHC.

chain with hydrogen transport and the cheapest supply chain with NH_3 transport. These two chains are outlined in red in Fig. 3.

For the other chemical hydrogen carriers (MeOH, DME, LOHC), the diagrams look very similar and show comparable cost ratios (see Appendix). The delivery of hydrogen by pipeline and truck (Conv-CGH_2-Pip-Truck) and the carrier transport via ship and truck (Carrier-Ship-Truck) remain the most cost-effective chains for the delivery of hydrogen and the carrier.

The most cost-effective supply chains were identified for all carriers and compared individually for each carrier (Fig. 4). Transporting the carrier is significantly cheaper than transporting hydrogen, resulting in a cost difference shown by the light orange bar in the middle of the four plots in Fig. 4. This cost difference corresponds to the upper marginal costs for an economically viable decentralized conversion plant. As long as a decentralized solution does not exceed these costs, it is worthwhile transporting the chemical hydrogen carrier to the point of use. There is also potential for cost reductions if decentralized solutions are developed with lower costs. However, if on-site conversion would be more expensive than these marginal costs, the carrier should possibly be converted centralized at the port and neat hydrogen should be transported.

The allowable specific costs are very similar for all carriers (around 1.2 €/kg_{H2}). However, a detailed analysis reveals differences in the costs for centralized conversion and compression. A comparison of the cost composition of the carriers shows that DME and MeOH incur higher conversion costs than LOHC and NH_3. This is due to the high investment costs associated with the required CO_2 capture. On the other hand, the compression costs for LOHC are significantly higher than for the other carriers. LOHC dehydrogenation takes place at low pressure, while the conversion of NH_3, MeOH and DME is carried out at higher pressures. As a result, LOHC has the highest compression demand after conversion to compress the hydrogen to the 80 bar required for the pipeline. Despite the different cost compositions, the total domestic supply costs of all carriers are in a similar range. It should be noted that no import costs for the carriers themselves were taken into account and are therefore not included in the calculated costs. Only the costs incurred between the port of import and the point of use are the focus of this study and are needed to estimate the potential of decentralized conversion.

Fig. 5 shows the allowable specific costs in relation to the costs of a centralized conversion plant. The cost ratio θ describes this relationship.

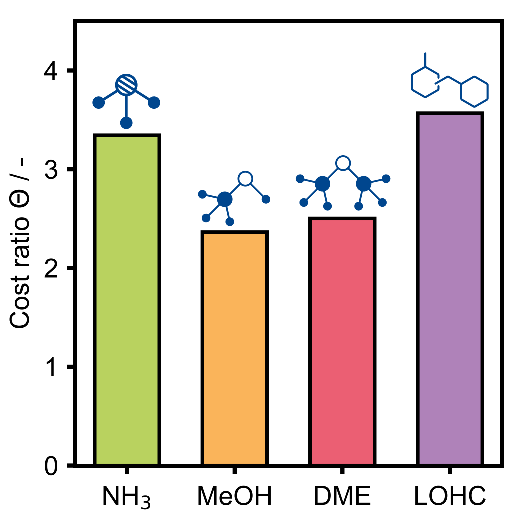

Fig. 5. Cost ratio θ of allowable specific costs for decentralized systems (from Fig. 4) and the costs of centralized conversion systems for the carriers NH_3, MeOH, DME and LOHC (distance = 800 km, last mile by truck = 50 km).

$$\theta = \frac{allowable\ specific\ costs}{centralized\ specific\ conversion\ cost} \quad 3.1$$

For the analysis, a hydrogen application was considered at a remote location in Bavaria (800 km away from the import port) with a last mile of 50 km to be bridged by truck for all intermodal transport modes. At this location, depending on the carrier, decentralized plants could cost 2.2 to 3.8 times more than centralized conversion plants (Fig. 5). This means that there is significant potential to reduce the cost of supply by transporting the carrier to the point of use.

4. Discussion

The calculation of the domestic supply chain costs, and the allowable specific costs depend on two aspects. First, the quality of data used in assumptions for a defined scenario and, second, the scenario itself or the resulting distances for the transport methods and the defined pipeline utilization. For this reason, the influence of the input parameters for a given scenario is first examined using sensitivity analysis and uncertainties. Then, the influence of the scenario parameters considered (distances and pipeline utilization) is analyzed in more detail. Finally, the calculated costs and the potential for cost reduction of decentralized conversion units are discussed with further influencing factors.

4.1. Uncertainty and sensitivity

Many assumptions have been made, while future costs or developments are subject to a high degree of uncertainty. All domestic supply chain costs are indicated with error bars (Figs. 3 and 4), which show the cost range of the supply chains and were calculated with uncertainties for each parameter (see Section 2.1.1). They show the results calculated under the best and worst assumptions for a given scenario with fixed distances. The intermodal hydrogen transport supply chains show very large error bars because the number of transport methods is higher and therefore also the number of assumptions used. Error bars for the transport of chemical hydrogen carriers are smaller overall, as the technology already exists and the overall costs are low.

In addition to the error bars, a calculation of the Impact Factor (IF) was carried out for each parameter to further investigate the calculated costs. The aim is to demonstrate the robustness of the results. To do this, first the sensitivity of each parameter on the result was calculated and then combined with the uncertainty of this parameter. For the sensitivity analysis, each parameter was changed by + - 30 % and the impact of changes on the calculated allowable specific costs for decentralized conversion plants were determined. The sensitivity φ is defined as:

$$\varphi_i = \frac{d\frac{C_{allowable}}{C_{allowable,Base}}}{d\frac{x}{x_{base}}} \quad 4.1$$

Positive sensitivity means that an increase in the parameter leads to an increase in the allowable specific costs. Negative sensitivity means that an increase in the parameters leads to a reduction in the allowable specific costs.

The result is very sensitive to changes in some parameters, which in many cases are fixed assumptions. However, other parameters are subject to uncertainties that must also be considered. A combination of sensitivities φ und uncertainties u (given in the appendix and described in Section 2.1.1) is needed and enables the calculation of the Impact Factor IF.

$$IF_i = \varphi_i * u_i \quad 4.2$$

The aim is to determine the parameters that have the greatest influence on the results and to evaluate this calculated influence. IF indicates the percentage by which the result would change if the parameter analyzed were at the edge of its uncertainty. This allowed us to identify all relevant parameters and to examine the robustness of the

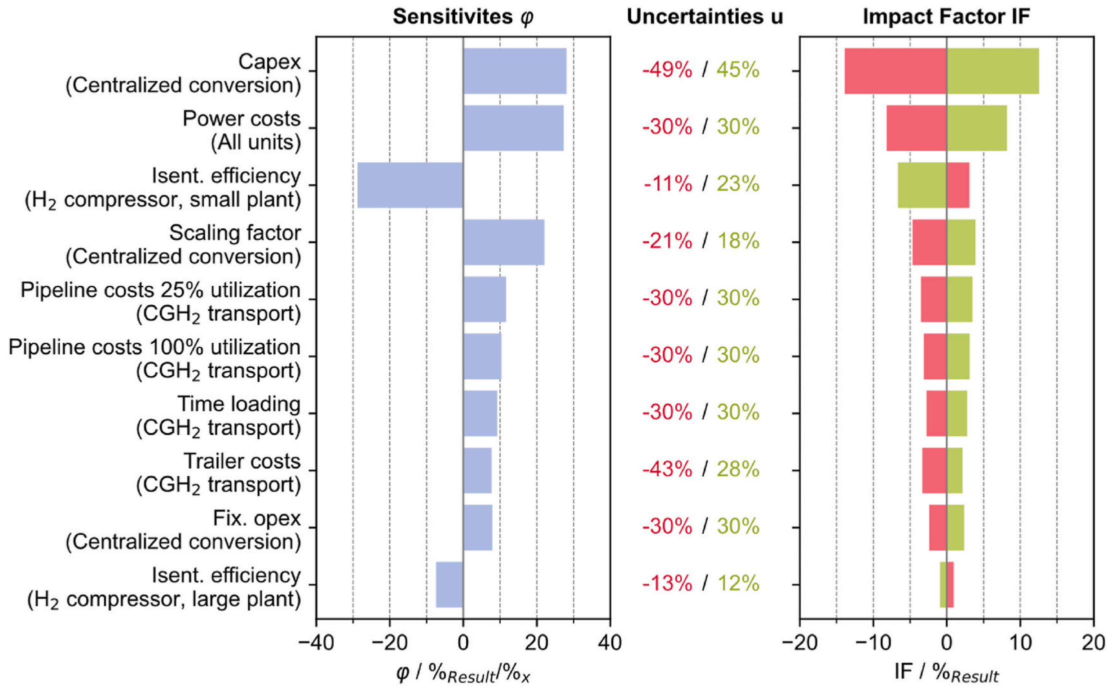

Fig. 6. The ten parameters with the greatest influence on the allowable specific costs of decentralized plants or with the greatest Impact Factor IF, plus the associated sensitivities φ and uncertainties u.

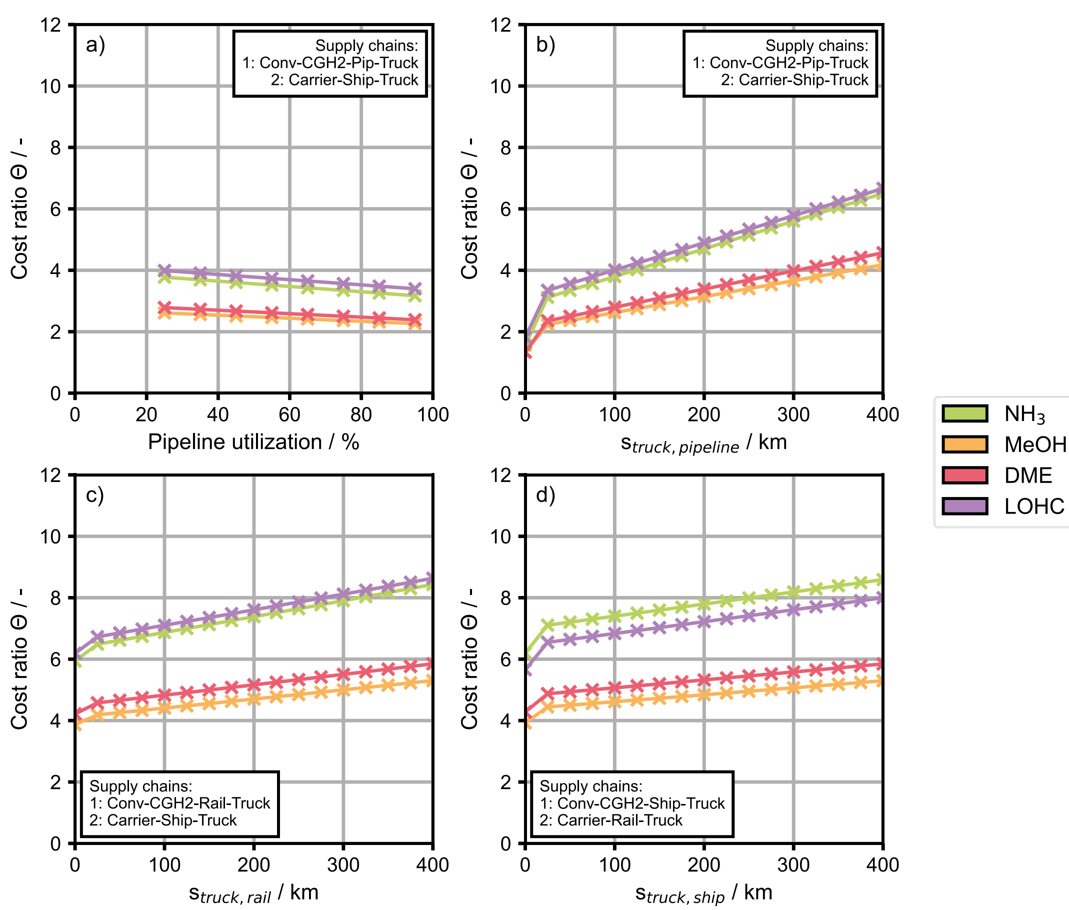

Fig. 7. – Cost ratio θ of allowable specific costs for decentralized conversion plants and the costs of centralized conversion plants for varying scenario parameters (total distance: 800 km). a) Pipeline utilization, b) Truck distance to the nearest pipeline, c) Truck distance to the nearest rail terminal, d) Truck distance to the nearest port. The supply chains used to calculate the allowable specific costs are fixed and are specified in the plots.

result depending on the number of parameters with a high influence and the order of magnitude of this influence.

Fig. 6 shows the sensitivities, uncertainties and the resulting Impact Factors for one scenario with NH_3 as carrier. The ten parameters with the highest Impact Factors are given. The Capex of the centralized conversion plant leads to the highest Impact Factor with a maximum influence on the result of 13 %. Only three other parameters lead to a change greater than 5 %. These parameters are the most critical ones where significant technical or economical changes would be most impactful on the results of this study. The small number of parameters with a significant Impact Factor IF shows that the resulting cost ratios are reliable, even though many assumptions were made. Although the calculated marginal costs should always be interpreted within the given range, the statements and conclusions regarding the potential of decentralized plants remain valid in a specific scenario.

4.2. Distances and pipeline utilization

The costs of the domestic supply chains and the allowable specific costs are calculated for a defined scenario with fixed distances and a specified pipeline utilization. Utilization depends on the expansion of the pipeline infrastructure and the time required for this, while distances depend on the location of the respective application. Both have a significant impact on the results.

For the scenario under consideration, a total distance of 800 km and a truck distance of 50 km were assumed in combination with other modes of transport (pipeline, rail, and ship). This assumption is optimistic, particularly with regard to the pipeline, as there is currently little information available on the locations of future hydrogen hubs that will transfer hydrogen from the pipeline to trailers. In addition, the pipeline must first be built, and even within Germany, the size of the pipeline network varies greatly between the federal states. Furthermore, the 50 km to the nearest rail terminal or port for reloading containers is not available at many locations. In principle, the rail network is larger than the federal waterway network, which means that the distance to the nearest rail terminal is likely to be shorter than to the nearest port in many cases. Nevertheless, 50 km is optimistic even for rail in many parts of Germany. The truck distance required for the last mile can be greater than the assumed 50 km in many cases.

To assess the influence of other scenarios on the calculated allowable specific costs and the resulting potential for decentralized plants, the scenario parameters were changed, and the cost ratio θ of allowable specific costs and centralized conversion costs were calculated (Fig. 7). The total distance was left at 800 km and only one scenario parameter was changed at a time – pipeline utilization (7.a), truck distance to nearest pipeline connection (7.b), truck distance to nearest rail terminal (7.c), truck distance to nearest port (7.d). The allowable specific costs can only be calculated using two supply chains. Accordingly, the supply chains used are kept constant for each analysis and are indicated in the diagrams for tracking purposes. Another sensitivity analysis, which varies the total distance as an input parameter, is also included in the appendix. The last mile distance is kept constant in this analysis, and the structure is based on Fig. 7.

As pipeline utilization increases, cost ratio θ decreases because pipeline costs fall and transporting hydrogen with upstream centralized conversion of the carrier becomes more attractive.

Increasing distance of the truck after the pipeline has a significant influence on the result. At a truck distance of zero, there is a direct pipeline connection, and the allowable specific costs result mainly from conversion and conditioning. It will be very difficult to meet these maximum marginal costs of the decentralized conversion plant, which is why centralized conversion would therefore be recommended. If there is no direct pipeline connection, the allowable specific costs increase significantly, and decentralized conversion becomes increasingly attractive.

The same trend can also be seen when the distance between truck and the nearest rail terminal and port changes. However, the influence is significantly lower than for pipelines. The allowable specific costs and cost ratio θ are generally at a significantly higher level than with the pipeline. This is due to the significantly higher transport costs for hydrogen by rail and truck (7.c) or by ship and truck (7.d) compared to pipelines and trucks (see Fig. 2). At a distance of zero, cost ratio θ again corresponds to the allowable specific costs if a rail terminal or port is located directly on site. There is still considerable potential for decentralized plants, as the costs are likely to be at least four times higher than those of the centralized conversion plant. However, this would require that there is no pipeline connection at all, and the value only applies to a total distance of 800 km.

4.3. Decentralized conversion costs

The cost differences in domestic supply chains lead to significant potential for cost reduction when the carrier is transported to the point of use. This finding remains valid even when considering the uncertainties of the assumptions and different scenarios or distances. Nevertheless, calculating the allowable specific costs or maximum possible costs of decentralized conversion plants does not guarantee savings. Depending on the application, decentralized systems can have different plant designs with different requirements, which also have a significant impact on costs. Some influencing factors lead to higher costs for decentralized plants, while others lead to further potential for cost reductions. The impact on costs must be worked out in detail during the development of decentralized technology for integrating chemical hydrogen carriers. This can only be done for specific applications, but the effects can be discussed in theory.

4.3.1. Influencing factors

Economy of scale vs. standardization: Large-scale plants are generally more cost-effective than small-scale plants due to economies of scale. Decentralized plants are therefore always more expensive than centralized plants. On the other hand, mass manufacturing or standardization could occur if decentralized plants are used in large numbers. However, this is unlikely, especially at the beginning of a technology rollout. Furthermore, standardization would make application-specific integration more difficult and is therefore not necessarily desirable.

Different plant designs: Not all technologies that are suitable for large-scale plants can be transferred to small-scale plants. In some cases, it is not possible to scale down the same process, meaning that a different design must be chosen (e.g. electrical heating instead of using large burners), which is likely to result in different costs. In addition, large-scale plants are mostly based on optimized processes, whereas the effort required for smaller plants is often too great to exploit all optimization possibilities.

Pressure requirements: Large-scale plants operate at high pressures because hydrogen must be transported at high pressures (in case of CGH_2). In most cases, the centralized plant feeds into the pipeline network, which operates at 80 bar. Transport by trailer or container requires even higher pressures of up to 500 bar. However, some applications might require significantly lower pressures or have no pressure requirements at all. Therefore, the conditioning step of hydrogen compression is not necessary for all applications or can be significantly reduced if the conversion takes place decentralized at the application site. This offers significant potential for costs reduction, as compressors are expensive in invest and operation. In addition, complexity and maintenance effort on site are reduced.

Purity requirements: A general hydrogen supply requires high purity levels, but a supply optimized for the specific application only needs to meet the requirements of that application. These could be the same as for the centralized conversion (e.g. fuel cell applications), but lower purity levels are possible for other applications. If hydrogen is required as a heat source, for example, the purity requirements are low, and the purification unit is no longer necessary. Depending on the application, only partial conversion may be necessary, or the carrier may be used directly. In this case, not only would the purification be designed differently, but the conversion step itself could also be designed differently.

Use case specific heat integration: Centralized plants are often designed as stand-alone facilities. Accordingly, they must provide the heat required for the endothermic conversion steps themselves. This leads to significant losses or lower conversion rates. Decentralized plants can be integrated into the respective applications. In industrial applications, residual heat may be available that can be used for endothermic reconversion reactions. The residual heat can be integrated into the conversion process and lead to higher efficiency.

Carbon capture/ CO_2-Transport: Organic chemical hydrogen carriers such as DME and MeOH bind hydrogen on CO_2 and use it as a carrier molecule. During reforming, CO_2 is released again. We assumed that centralized plants would capture the CO_2 for possible back transport to the synthesis site or for carbon capture and storage (CSS). However, decentralized plants must also deal with CO_2 management. If the CO_2 source is renewable (biomass or direct air capture) the CO_2 can be released back into the air during reforming. If, as in centralized plants, a closed CO_2 cycle is desired or the source is not renewable, the CO_2 must be captured and transported. This leads to an additional effort and additional costs and might limit carbon-based carriers in decentralized applications with current CC technology.

5. Summary and conclusions

The aim of this study was to investigate the possible transport options of chemical hydrogen carriers after their import and to evaluate the potential of decentralized conversion plants. To supply an application with hydrogen, the carriers can either be converted centralized at the port and the hydrogen transported as CGH_2 or LH_2, or the carrier can be transported to the application and converted on site. If a pipeline connection is available at the point of use, transporting CGH_2 via pipeline is the best option. If no pipeline connection is available, transporting CGH_2 quickly becomes expensive and therefore less attractive. We calculated and compared the costs of the various domestic supply options from the port of import to the point of use. The cost difference resulting from the cheaper transport of the carriers compared to the conversion, conditioning, and transport of CGH_2 and LH_2 represents the allowable specific costs that decentralized conversion may incur. These were determined in this study for a specific scenario. Using our method, it is possible to estimate the potential for decentralized conversion plants at an early stage of development for a given location and pipeline utilization. The following key findings can be formulated.

- In most cases, the transport of CGH_2 leads to very high costs (direct pipeline connection excluded). Transporting CGH_2 by truck alone is the most expensive transport option calculated. However, costs can be significantly reduced by combining pipelines and low-distance transport by truck.
- Transporting LH_2 is significantly cheaper than transporting CGH_2, but the high costs of liquefaction compared to compression negate the cost advantage. However, LH_2 can still be a viable option if the application requires LH_2 or if LH_2 is imported directly.
- NH_3 results in the lowest specific transport costs with regard to the chemically bound hydrogen. If the hydrogen released during reforming with water is also taken into account, DME results in the lowest specific transport costs.
- The transport costs of LOHC are significantly lower than those of CGH_2, but considerably higher than those of the other carriers. This is due to the high mass of the carrier molecule and the resulting low amount of hydrogen transported. However, LOHC is the easiest carrier to handle and therefore has a major practical advantage over the other chemical hydrogen carriers and hydrogen.
- A comparison of the various domestic supply chains leads to the same two most cost-effective supply chains for each carrier examined: transport of CGH2 by pipeline and truck as a supply chain with centralized conversion, and transport by ship and truck for delivery of the carrier.
- The cost differences, taking into account conversion and conditioning costs at the port, result in high allowable specific costs for decentralized plants. For a total distance of 800 km and a pipeline connection 50 km away from the application, decentralized conversion plants for all chemical hydrogen carrier examined can cost around 1.2 €/kg_{H2} specifically. This means they can cost 2.2 to 3.8 times more than centralized conversion plants. If the pipeline is further away or not available at all, the allowable specific costs rise to 5 to 8 times the centralized conversion costs.
- The allowable specific costs and thus the potential for decentralized conversion plants depend heavily on the location of the application and the local supply options. They must be determined individually for each location.
- Decentralized conversion plants can be designed differently than centralized plants, depending on the application. This can lead to additional costs but also offers further cost savings. Decentralized plants are most attractive for applications with low pressure and purity requirements and for applications where waste heat is available (e.g., in high-temperature applications).

For many locations, it can be very attractive to have the carriers delivered to the site and to aim for decentralized conversion and integration. In this study, a methodology was developed to evaluate locations and estimate the potential at an early stage of development. The next step should be to develop technical solutions for decentralized systems for specific use cases at identified locations with high-cost reduction potentials and compare the costs with the maximum costs calculated in this study.

CRediT authorship contribution statement

Oliver Ulrich: Writing – original draft, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization. **Philipp Morsch:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Andreas Peschel:** Writing – review & editing, Supervision, Methodology.

Decleration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used DeepL in order to improve language. After using this toll/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content in this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

[1] Bundesministerium für Wirtschaft und Energie (BMWi). In: Die Nationale Wasserstoffstrategie; 2020. https://www.bundeswirtschaftsministerium.de/Redaktion/DE/Publikationen/Energie/die-nationale-wasserstoffstrategie.pdf?__blob=publicationFile&v11.
[2] Bundesministerium für Wirtschaft und Klimaschutz (BMWK). In: Importstrategie für Wasserstoff und Wasserstoffderivate; 2024.
[3] Schulte S, Schönfisch M, Brändle G. Wasserstoff: Bezugsoptionen für Deutschland. Kostenvergleich von importiertem und lokal produziertem CO2- armen Wasserstoff. 2020. https://www.ewi.uni-koeln.de/cms/wp-content/uploads/2021/01/EWI_Policy_Brief_H2_Supply_Costs_20201127.pdf.
[4] Sterner M, Hofrichter A, Meisinger A, Bauer F, Pinkwart K, Maletzko A, et al. 19 import options for green hydrogen and derivatives - an overview of efficiencies and technology readiness levels. Int J Hydrogen Energy 2024;90:1112–27. https://doi.org/10.1016/j.ijhydene.2024.10.045.
[5] Industrie Agora, Hamburg TU. Wasserstoff-Importoptionen für Deutschland: analyse mit einer Vertiefung zu Synthetischem Erdgas (SNG) bei nahezu geschlossenem Kohlenstoffkreislauf. https://www.agora-energiewende.de/fileadmin/Projekte/2022/A-EW_306_SNG_Imports_WEB.pdf; 2023.
[6] Hampp J, Düren M, Brown T. Import options for chemical energy carriers from renewable sources to Germany. PLoS One 2023;18(2):e0262340. https://doi.org/10.1371/journal.pone.0281380.
[7] IRENA. In: Global Hydrogen trade to meet the 1.5°C climate goal: part 2: technology review of hydrogen carriers; 2022. https://india-re-navigator.com/public/uploads/1651644555-IRENA_Global_Trade_Hydrogen_2022.pdf.
[8] FfE, Ed. Wasserstofftransportoptionen. https://www.ffe.de/veroeffentlichungen/wasserstofftransport-analyse-der-prozessketten-kostenbewertung-und-gegenueberstellender-vergleich/; 2022.
[9] Roth S, Abdelrahman O, Hüllhorst T, Sari K, Griffith H, Matthes C, et al. Bulk transport options for green molecules: focus area: europe and MENA Region. https://www.solarpaces.org/wp-content/uploads/2024/02/MENA-2024-Dii-Bulk-Transport-Options-for-Green-Molecules.pdf; 2024.
[10] KHI-built LH2 carrier. SUISO FRONTIER, classified by ClassNK SEA-Japan 2022; 411:1–2. https://www.jsea.or.jp/wp_2022/wp-content/uploads/2022/02/SEA-Japan-No.-411.pdf.
[11] Hank C, Holst M, Thelen C, Kost C, Längle S, Schaadt A, et al. Power-to-X Country analyses: Site-specific, comparative analysis for suitable Power-to-X pathways and products in developing and emerging countries. https://www.ise.fraunhofer.de/en/publications/studies/power-to-x-country-analyses.html; 2023.
[12] Pfennig M, Böttger D, Häckner B, Geiger D, Zink C, Bisevic A, et al. Global GIS-based potential analysis and cost assessment of Power-to-X fuels in 2050. Appl Energy 2023;347:121289. https://doi.org/10.1016/j.apenergy.2023.121289.
[13] Lee J-S, Cherif A, Yoon H-J, Seo S-K, Bae J-E, Shin H-J, et al. Large-scale overseas transportation of hydrogen: comparative techno-economic and environmental investigation. Renew Sustain Energy Rev 2022;165:112556. https://doi.org/10.1016/j.rser.2022.112556.
[14] Weikl M, Peschel A. Industrial view on hydrogen carriers for intercontinental transport. Curr Opin Green Sustainable Chem 2023;44:100843. https://doi.org/10.1016/j.cogsc.2023.100843.
[15] HPA Hamburg Port Authority. Sustainable Energy Hub zur Förderung der Energiewende. https://www.hamburg-port-authority.de/fileadmin/user_upload/seh/SEH_2024_deu.pdf. [Accessed 23 May 2025].
[16] Uniper. Green-Wilhelmshaven: Auf zu neuen Horizonten. https://www.uniper.energy/de/loesungen/energy-transformation-hubs/energy-transformation-hub-nordwest/green-wilhelmshaven. [Accessed 23 May 2025].
[17] Fraunhofer Institut für Schicht- und Oberflächentechnik IST. In: Kurzfristige Lösungen für grünen Wasserstoff in Salzgitter – thesenpapier GreenH2 SZ; 2022.
[18] G. Di Lullo, T. Giwa, A. Okunlola, M. Davis, T. Mehedi, A.O. Oni et al. Large-scale long-distance land-based hydrogen transportation systems: a comparative techno-economic and greenhouse gas emission assessment.
[19] Institute of Energy Economics at the University of Cologne gGmbH (EWI). In: Regionalization of Hydrogen Scenarios: a comparative analysis of demand, infrastructure and supply; 2024. https://www.ewi.uni-koeln.de/cms/wp-content/uploads/2024/11/20241125_EWI_RegionalizationofHydrogenScenarios_final.pdf.
[20] Sens L, Neuling U, Wilbrand K, Kaltschmitt M. Conditioned hydrogen for a green hydrogen supply for heavy duty-vehicles in 2030 and 2050 – a techno-economic well-to-tank assessment of various supply chains. Int J Hydrogen Energy 2024;52: 1185–207. https://doi.org/10.1016/j.ijhydene.2022.07.113.
[21] Busch T, Groß T, Linßen J, Stolten D. The role of liquid hydrogen in integrated energy systems–A case study for Germany. Int J Hydrogen Energy 2023;48(99): 39408–24. https://doi.org/10.1016/j.ijhydene.2023.05.308.
[22] Borsboom-Hanson T, Patlolla SR, Herrera OE, Mérida W. Point-to-point transportation: the economics of hydrogen export. Int J Hydrogen Energy 2022;47 (74):31541–50. https://doi.org/10.1016/j.ijhydene.2022.07.093.
[23] Xu Z, Zhao N, Yan Y, Zhang Y, Zhang T, Wu D, et al. Hydrogen supply chain for future hydrogen-fuelled railway in the UK: transport sector focused. Int J Hydrogen Energy 2024;86:1–13. https://doi.org/10.1016/j.ijhydene.2024.08.397.
[24] Scheffler F, Imdahl C, Zellmer S, Herrmann C. Techno-economic and environmental assessment of renewable hydrogen import routes from overseas in 2030. Appl Energy 2025;380:125073. https://doi.org/10.1016/j.apenergy.2024.125073.
[25] Rapp J, Eckert S, Faltenbacher M, Panik MS, Panik F, Machens C. Untersuchung und Bewertung möglicher zukünftiger Importrouten für grünen Wasserstoff in die Region Stuttgart. H2 GeNeSiS, https://h2genesis.region-stuttgart.de/wp-content/uploads/2023/09/WRS-H2-Importstudie.pdf; 2023.
[26] Eißler T, Groos U, Holst M, Deringer P, Edenhofer L, Mendler F, et al. Optimizing the supply chain for green hydrogen and derivatives: a case study from Australia to Germany including inland transport considerations. Int J Hydrogen Energy 2025. https://doi.org/10.1016/j.ijhydene.2025.04.163.
[27] Spillmann T, Nolden C, Ragwitz M, Pieton N, Sander P, Rublack L, et al. Wasserstoff-Verteiloptionen 2035. https://publica.fraunhofer.de/entities/publication/5c8f49b8-cb82-489e-a49d-575130265629; 2024.
[28] International AACE, editor. Cost estimate classification System – as applied in engineering, procurement, and construction for the process industries PROCESS INDUSTRIES: recommended practice no. 18R-97; 2005. https://aheinc.ca/wp-content/uploads/2018/12/AACE-Cost-Estimate-Classification-System.pdf.
[29] Spatolisano E, Restelli F, Matichecchia A, Pellegrini LA, Angelis AR de, Cattaneo S, et al. Assessing opportunities and weaknesses of green hydrogen transport via LOHC through a detailed techno-economic analysis. Int J Hydrogen Energy 2024; 52:703–17. https://doi.org/10.1016/j.ijhydene.2023.08.040.
[30] Teichmann D, Arlt W, Wasserscheid P. Liquid Organic Hydrogen Carriers as an efficient vector for the transport and storage of renewable energy. Int J Hydrogen Energy 2012;37(23):18118–32. https://doi.org/10.1016/j.ijhydene.2012.08.066.
[31] Tsiklios C, Hermesmann M, Müller TE. Hydrogen transport in large-scale transmission pipeline networks: thermodynamic and environmental assessment of repurposed and new pipeline configurations. Appl Energy 2022;327:120097. https://doi.org/10.1016/j.apenergy.2022.120097.
[32] Statista. Industriestrompreise (inklusive Stromsteuer) in Deutschland in den Jahren 1998 bis. https://de.statista.com/statistik/daten/studie/252029/umfrage/industriestrompreise-inkl-stromsteuer-in-deutschland. [Accessed 22 May 2025].
[33] thyssenkrupp uhde. Ammonia cracking. https://www.thyssenkrupp-uhde.com/en/ammonia-cracking. [Accessed 9 July 2025].
[34] KBR. Empowering Transition H2ACT: Ammonia Cracking Technology: a pathway to sustainable energy. 2023. https://scic.sg/images/KBR_Ammonia_Cracking_H2ACT_SCIC_2023_20231018.pdf [accessed 22 May 2025].
[35] Stylianou E. KBR Ammonia Cracking, H2ACTSM - a roadmap from clean energy source to sustainable hydrogen supply. https://www.kbr.com/sites/default/files/documents/2023-10/TechnicalJournal2023_2022_KBR_Ammonia_Cracking_H2ACT_Roadmap_Clean_Eenrgy_Source_Sustianable_Hydrogen_Supply_0.pdf. [Accessed 22 May 2025]. sites/default/files/documents/2023-10/TechnicalJournal2023_2022_KBR_Ammonia_Cracking_H2ACT_Roadmap_.
[36] Oni AO, Anaya K, Giwa T, Di Lullo G, Kumar A. Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions. Energy Convers Manag 2022;254:115245. https://doi.org/10.1016/j.enconman.2022.115245.
[37] Mahler Ags GmbH. Hydrogen generation by methanol reforming | Mahler AGS, https://www.mahler-ags.com/plants/hydrogen-plant-hydroform-m; [accessed 25 May 2025].
[38] Ruther T, Stadler H, Peschel A. Potential of high-temperature steam reforming for enabling DME as a hydrogen carrier. https://doi.org/10.1016/j.cej.2025.168929.
[39] IEAGHG. In: IEAGHG technical report 2017-02: techno - economic evaluation of SMR based standalone (Merchant) hydrogen plant with CCS; 2017.
[40] Schühle P, Stöber R, Gierse M, Schaadt A, Szolak R, Thill S, et al. Dimethyl ether/ CO 2 – a hitherto underestimated H 2 storage cycle. Energy Environ Sci 2023;16 (7):3002–13. https://doi.org/10.1039/D3EE00228D.
[41] Papadias DD, Peng J-K, Ahluwalia RK. Hydrogen carriers: production, transmission, decomposition, and storage. Int J Hydrogen Energy 2021;46(47): 24169–89. https://doi.org/10.1016/j.ijhydene.2021.05.002.
[42] Niermann M, Timmerberg S, Drünert S, Kaltschmitt M. Liquid Organic Hydrogen Carriers and alternatives for international transport of renewable hydrogen. Renew Sustain Energy Rev 2021;135:110171. https://doi.org/10.1016/j.rser.2020.110171.
[43] Distel MM, Margutti JM, Obermeier J, Nuß A, Baumeister I, Hritsyshyna M, et al. Large-Scale H 2 storage and transport with liquid organic hydrogen carrier technology: insights into Current Project developments and the future outlook. Energy Tech 2025;13(2). https://doi.org/10.1002/ente.202301042.
[44] Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung. Offizieller DAC-Umrechnungskurs: oda-zahlen, https://www.bmz.de/de/ministerium/zahlen-fakten/oda-zahlen/hintergrund/dac-umrechnungskurs-35300; [accessed 18 September 2025].
[45] Neumann & Esser. Piston compressors. https://www.neuman-esser.com/en/products-services/compressors-compressor-systems/piston-compressors [acsessed 9 July 2025].
[46] U.S. Department of Energy. In: Hydrogen and fuel cell technologies office multi-year research: development and demonstration plan: 3.2 hydrogen delivery; 2015. https://www.energy.gov/sites/prod/files/2015/08/f25/fcto_myrdd_delivery.pdf.
[47] Khan MA, Young C, Mackinnon C, Layzell DB. The techno-economics of hydrogen compression: the techno-economics of hydrogen compression. https://transitionaccelerator.ca/wp-content/uploads/2023/04/TA-Technical-Brief-1.1_TEEA-Hydrogen-Compression_PUBLISHED.pdf; 2021.
[48] Tan-Ping C, Air Liquide. Chevron technology venture, gas technology Institute, NREL. In: Final report - hydrogen delivery infrastructure options analysis: DOE

award number: DE-FG36-05GO15032; 2008. Tiax et al. https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/delivery_infrastructure_analysis.pdf.
[49] Cardella UF. Large-scale hydrogen liquefaction under the aspect of economic viability. 2018. Dissertation, TU München.
[50] Restelli F, Spatolisano E, Pellegrini LA, Cattaneo S, Angelis AR de, Lainati A, et al. Liquefied hydrogen value chain: a detailed techno-economic evaluation for its application in the industrial and mobility sectors. Int J Hydrogen Energy 2024;52:454–66. https://doi.org/10.1016/j.ijhydene.2023.10.107.
[51] Peschel A. Industrial perspective on hydrogen purification, compression, storage, and distribution. Fuel Cells 2020;20(4):385–93. https://doi.org/10.1002/fuce.201900235.
[52] Ortiz Cebolla R, Dolci F, Weidner E. Assessment of hydrogen delivery options: feasibility of transport of green hydrogen within Europe. https://publications.jrc.ec.europa.eu/repository/handle/JRC130442; 2022.
[53] Reuß M, Grube T, Robinius M, Preuster P, Wasserscheid P, Stolten D. Seasonal storage and alternative carriers: a flexible hydrogen supply chain model. Appl Energy 2017;200:290–302. https://doi.org/10.1016/j.apenergy.2017.05.050.
[54] Parolin F, Colbertaldo P, Campanari S. Development of a multi-modality hydrogen delivery infrastructure: an optimization model for design and operation. Energy Convers Manag 2022;266:115650. https://doi.org/10.1016/j.enconman.2022.115650.
[55] Stolzenburg K, Mubbala R. Integrated design for demonstration of efficient liquefaction of hydrogen. IDEALHY) 2013. https://www.idealhy.eu/uploads/documents/IDEALHY_D3-16_Liquefaction_Report_web.pdf.
[56] Bundesamt für Logistik und Mobilität. Sonn- und Feiertagsfahrverbot in Deutschland. https://www.balm.bund.de/DE/Themen/RechtsentwicklungRechtsvorschriften/Rechtsvorschriften/Strassenverkehrsrecht/LKW-Fahrverbote/LKW-Fahrverbote_node.html; [accessed 22 May 2025].
[57] Hurskainen M, Ihonen J. Techno-economic feasibility of road transport of hydrogen using liquid organic hydrogen carriers. Int J Hydrogen Energy 2020;45(56):32098–112. https://doi.org/10.1016/j.ijhydene.2020.08.186.
[58] Reuß M, Dimos P, Léon A, Grube T, Robinius M, Stolten D. Hydrogen road transport analysis in the energy System: a case Study for Germany through 2050. Energies 2021;14(11):3166. https://doi.org/10.3390/en14113166.
[59] Danish Energy Agency and Energinet, Ed. Energy transport: technology descriptions and projections for long-term energy system planning., https://ens.dk/technologydata.
[60] Reddi K, Elgowainy A, Rustagi N, Gupta E. Techno-economic analysis of conventional and advanced high-pressure tube trailer configurations for compressed hydrogen gas transportation and refueling. Int J Hydrogen Energy 2018;43(9):4428–38. https://doi.org/10.1016/j.ijhydene.2018.01.049.
[61] TransHyDE. Synthesebericht des TransHyDE- Projekts LNG2Hydrogen: erarbeitung einer wissenschaftlich fundierten, nachhaltigen Datenbasis und Empfehlung als Entscheidungsbasis für die zukunftsfähige und langfristige Nutzung von LNG-Terminal-Standorten als logistische Knotenpunkte für Wasserstoff und dessen Transportvektoren. https://www.wasserstoff-leitprojekte.de/lw_resource/datapool/systemfiles/elements/. file. s/9842531e-7c28-11f0-9a65-fa163e7d9971/live/document/250813_LNG2Hydrogen_Whitepaper-final_. V3.pdf.
[62] Decker L. Liquid hydrogen distribution technology: HYPER closing seminar. https://www.sintef.no/globalassets/project/hyper/presentations-day-2/day2_1105_decker_liquid-hydrogen-distribution-technology_linde.pdf; 2019 [accessed 22 May 2025].
[63] van der Meulen S, Grijspaardt T, Mars W, van der Geest W, Roest-Crollios A, Kiel J. Cost figures for Freight Transport - final report: kostenkengetallen voor Goederenvervoer - eindrapportage. 2023.
[64] CAMPFIRE/AmmoRef. Ammoniak als Kraftstoff und Energiespeicher für die Dekarbonisierung des Energiesystems: Innovative Technologien und nachhaltige Wertschöpfungsketten. https://; 2025. www.wasserstoff-leitpro. jekte.de/lw_resource/datapool/systemfiles/elements/files/05570d0d-66df-11f0-b33d-fa163e7d9971/live/document/Ammoniak-als-Kraftstoff-und-Energiespeicher-fuer-die-. Dekarbonisierung-. des-. Energiesystems.pdf.
[65] Häfen und Güterverkehr Köln AG. Zukunftweisendes Pionierprojekt in der Binnenschifffahrt: HGK Shipping entwickelt Europas erstes Gastankschiff zum Transport von kalt verflüssigtem Ammoniak und LCO2. https://www.hgk.de/fileadmin/pressemitteilungen/2024/2024_04_17_PM_HGK_Shipping_Pionierschiff.pdf. [Accessed 9 July 2024].
[66] NRW.Global business. Port of Duisburg to become hydrogen hub. https://www.nrwglobalbusiness.com/about-us/press/detail/port-of-duisburg-to-become-hydrogen-hub. [Accessed 9 July 2025].
[67] Containerterminal Salzburg GmbH. Terminaltarif 2025. https://www.ct-sbg.at/cts_de/downloads. [Accessed 9 July 2025].
[68] Wiencont. Konditionen umschlag. https://www.wiencont.com/umschlag. [Accessed 9 July 2025].
[69] Wang A, Jens J, Mavins D, Moultak M, Schimmel M, van der Leun K, et al. European Hydrogen Backbone: analysing future demand. Supply, and transport of hydrogenEuropean. 2021. https://ehb.eu/files/downloads/EHB-Analysing-the-future-demand-supply-and-transport-of-hydrogen-June-2021-v3.pdf.
[70] van Rossum R, Jens J, La Guardia G, Wang A, Kühnen L, Overgaag M. European Hydrogen Backbone: a european hydrogen infrastructure vision covering 28 countries. https://ehb.eu/files/downloads/ehb-report-220428-17h00-interactive-1.pdf; 2022.