TUHH | IUE

Agora Industry

Agora Energiewende

Hydrogen import options for Germany

Analysis with an in-depth look at synthetic natural gas (SNG) with a nearly closed carbon cycle

BERLIN, OCTOBER 2023

Underlying publication

Full analysis with all assumptions in German only	Agora conclusions in English
	
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Structure

1.	Conclusions by Agora Industry
2.	Analysis by Hamburg University of Technology (TUHH) / Institute of Environmental Technology and Energy Economics (IUE)

Conclusions by Agora Industry

Policy should focus on no-regret hydrogen applications which clearly need hydrogen or derivatives to become climate-neutral

Green molecules needed?	Industry	Transport	Power sector	Buildings
No-regret	· Reaction agents (DRI steel) · Feedstock (ammonia, chemicals)	· Long-haul aviation · Maritime shipping	· Renewable energy back-up depending on wind and solar share and seasonal demand structure	· Heating grids (residual heat load *)
Controversial	· High-temperature heat	· Trucks and buses ** · Short-haul aviation and shipping · Trains ***	· Absolute size of need given other flexibility and storage options	
Bad idea	· Low-temperature heat	· Cars · Light-duty vehicles		· Building-level heating

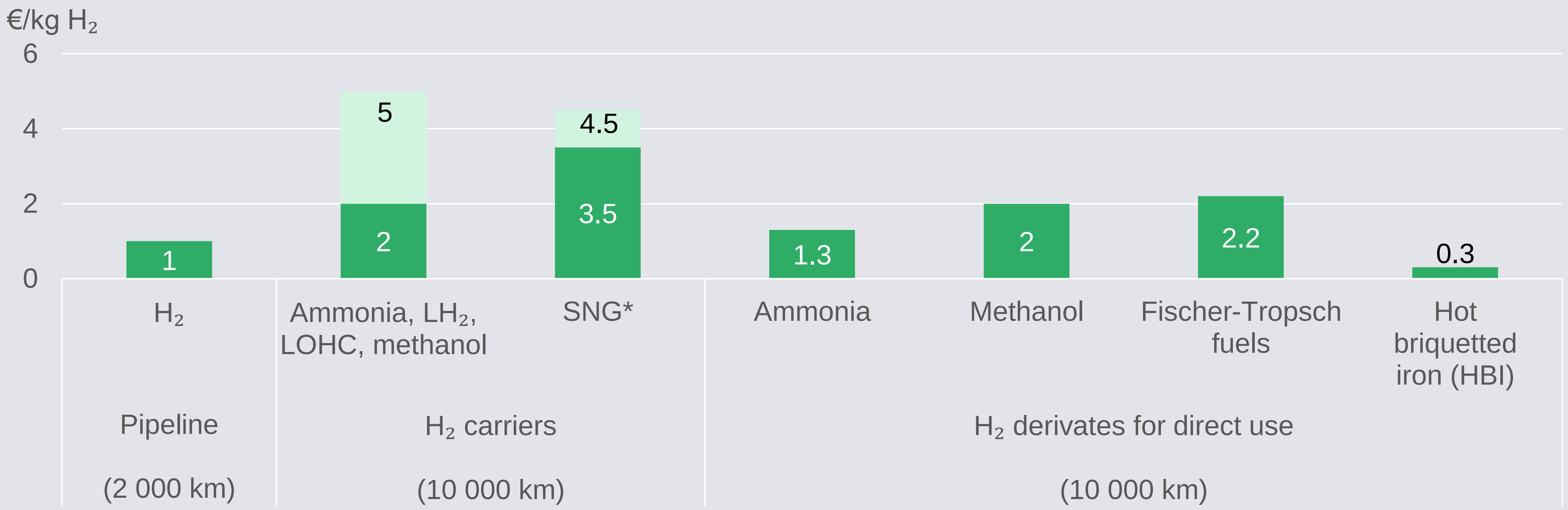
* After using renewable energy, ambient and waste heat as much as possible. Especially relevant for large existing district heating systems with high flow temperatures. Note that according to the UNFCCC Common Reporting Format, district heating is classified as being part of the power sector.

** Series production currently more advanced on electric than on hydrogen for heavy duty vehicles and buses. Hydrogen heavy duty to be deployed at this point in time only in locations with synergies (ports, industry clusters).

*** Depending on distance, frequency and energy supply options

Pipelines have the lowest H_2 transport cost. H_2 derivates like ammonia or HBI which can be processed directly, can be more cost-effective. H_2 carriers have higher transport cost

Hydrogen transport cost to Germany 2030 in €/kg, including conversion losses, but excluding hydrogen production cost (LCOH)



Agora Industry (2023) based on TUHH (2023), Acatech (2022), Agora Industry & Wuppertal Institute (2023); Different shades of green represent minimum and maximum values, respectively; * SNG with a nearly closed carbon cycle; HBI without CAPEX of DRI installations and ships that would be needed anyway in an alternative scenario;

Technological innovation is a decisive prerequisite for all import options, except H_2 pipelines and ammonia for direct use

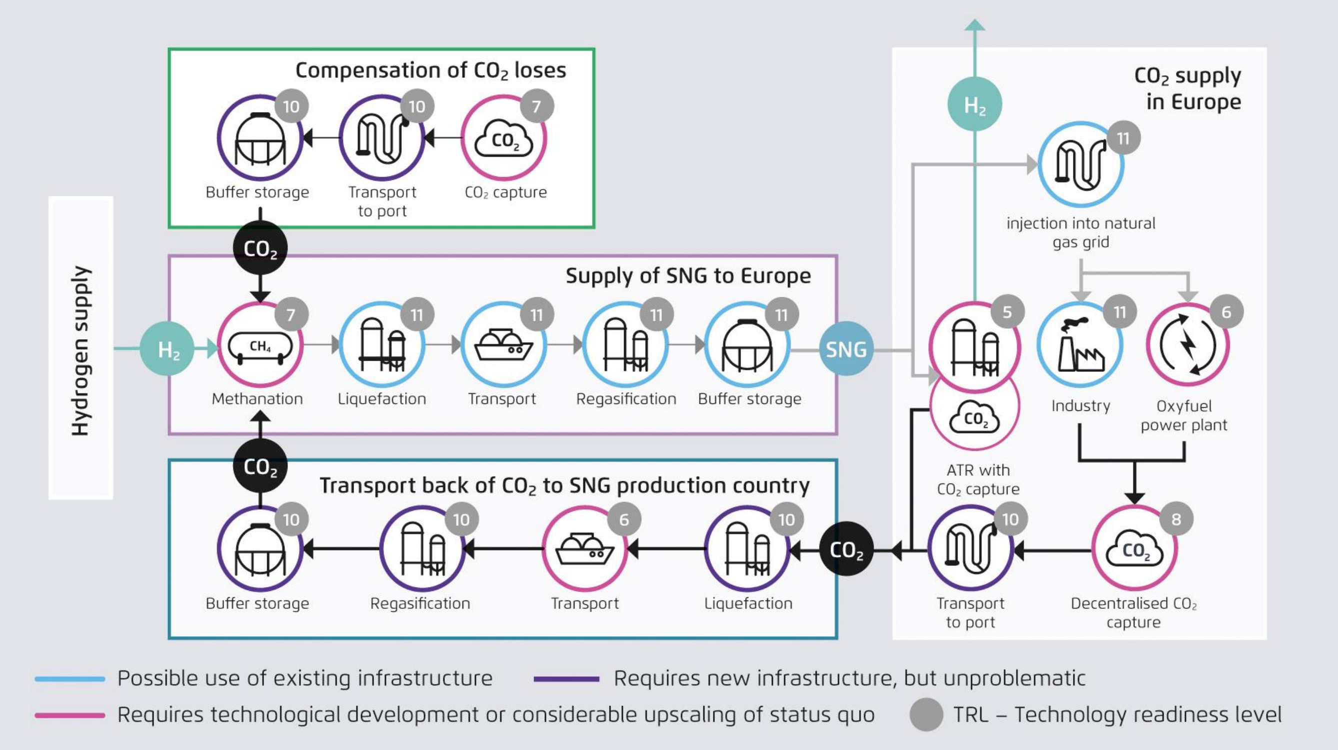
Comparison of hydrogen import options

Form of transport	H_2 pipeline	Shipping		
Transport good	Elementary H_2	H_2 carrier		H_2 derivates for direct use
Variants	Re-purposed, newly built	Ammonia (NH_3), LH_2, LOHC, methanol (MeOH)	SNG with nearly closed carbon cycle	Ammonia (NH_3), methanol (MeOH), FT products, Hot briquetted iron (HBI)
Technology readiness level [1 low–11 high]*	8 re-assignment 10 new built	4 NH_3 cracker (large) 7 LH_2 tanker 3 LH_2 bunkering 6–7 LOHC molecule 11 LOHC tanker	7 catalytic methanation 5 autothermal reforming 4–7 CO_2 shipping n.a. Dual gas carrier for SNG/CO_2 6–7 Direct Air Capture 5–6 oxyfuel gas plant	11 NH_3 tanker 6–7 Direct Air Capture 6 HBI: H_2-based direct reduction of iron ore (DRI)
Implementation horizon in years**	3–5 re-purposed 8–10 new built	6–10	10	2 (NH_3)–10

* based on IEA (2023); autothermal reforming with carbon capture; important TRL 4-6: prototype; 7-8: demonstration; 9: commercial operation in relevant environment ** based on Acatech (2022), Prognos et al. (2023)

SNG with a nearly closed carbon cycle as a hydrogen carrier faces three challenges

Components of the SNG supply chain with a nearly closed carbon cycle and TRLs



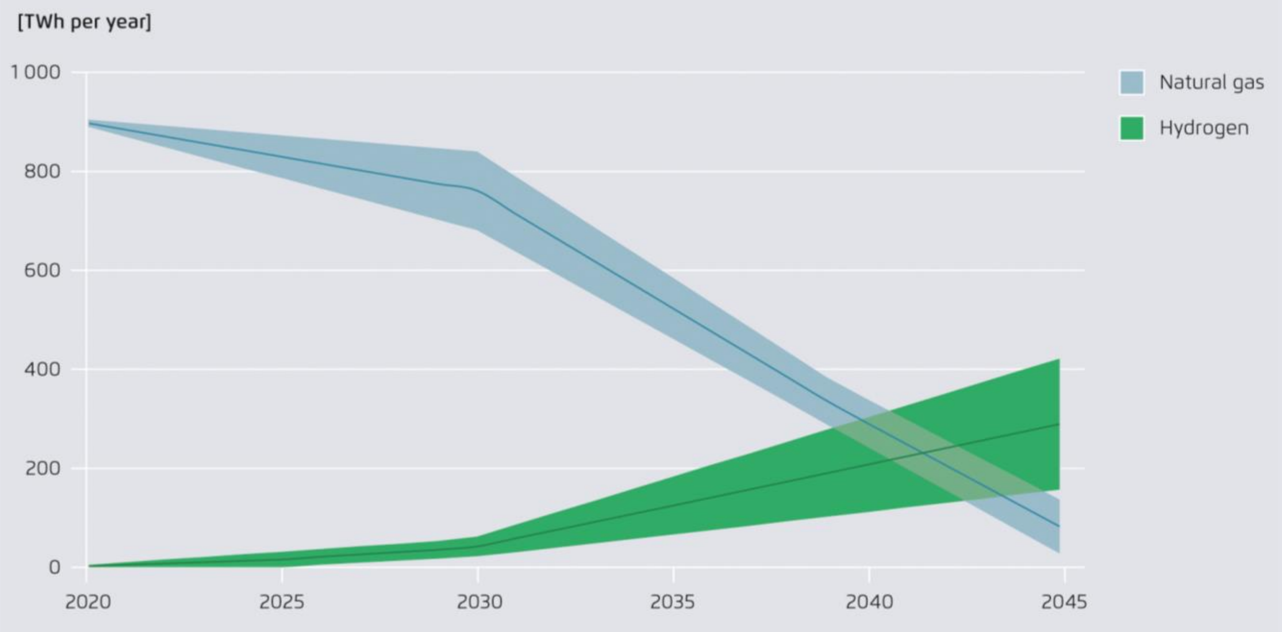
TUHH (2023): CO_2 = Carbon dioxide, H_2 = Hydrogen, O_2 = Oxygen, SNG = Synthetic natural gas, ATR = Autothermal reforming.

1. A complex interplay of several components with a comparatively low level of technology readiness and an implementation period of ten years;
2. Competition with other import options that could prove cheaper than SNG in the medium term;
3. Regulatory uncertainty regarding the measurement, reporting and verification of international carbon flows.

TRLs are based on the IEA's ETP Clean Energy Technology Guide. Important TRLs: 4–6: Prototype; 7–8: Demonstration; 9: Commercial operation in relevant environment

Short-term use of existing natural gas grids for transporting SNG could pose a risk to the energy transition if as a result the necessary repurposing of methane pipelines for H_2 is delayed

Energy demand for natural gas (incl. biogas) and hydrogen
in different climate-neutrality scenarios for Germany in TWh per year



Agora Energiewende (2023) with scenarios from Agora Energiewende (2021), Ariadne (2021), BDI (2021), BMWK (2022), dena (2021)

- → In view of their critical importance, the emphasis in Germany should be on conversion to and construction of hydrogen pipelines.
- → The creation of new CO_2 infrastructure should focus on no-regret CCS applications: unavoidable process emissions from cement and limestone production as well as emissions from waste incineration.

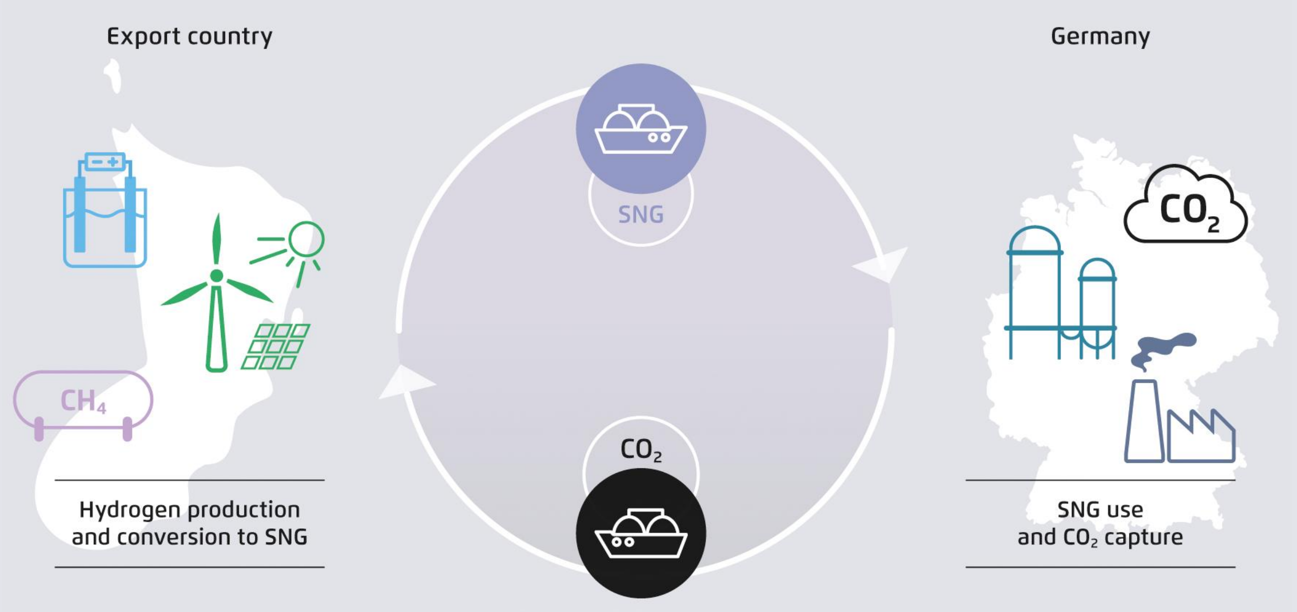
Conclusions at a glance

1	**Germany will need sufficient hydrogen imports to achieve its goal of climate neutrality in the power sector by 2035 and to decarbonise the steel and chemical industries.** According to the National Hydrogen Strategy, imports of at least 45 TWh of hydrogen per year will be needed from 2030. In addition to pipeline imports, other hydrogen carriers could also be imported by ship.
2	**At a cost of < € 1/kg H_2, pipelines are the cheapest way of importing pure hydrogen**. Importing hydrogen carriers by ship increases the cost of transport, following reconversion, to roughly €2 to 5/kg H_2. Hydrogen derivatives such as ammonia or hot briquetted iron (HBI) that can be further processed directly constitute a cost-effective alternative in many cases (< €1.5/kg H_2). Technological innovations are a key prerequisite for all import options, with the exception of hydrogen pipelines and ammonia for immediate use.
3	**Using synthetic natural gas (SNG) with a nearly closed carbon cycle as a hydrogen carrier entails three challenges:** (1) the complex interplay of several components with a comparatively low level of technology readiness and an implementation period of ten years; (2) competition with other import options that could prove cheaper than SNG in the medium term; (3) regulatory uncertainty regarding the measurement, reporting and verification of international carbon flows.
4	**Short-term use of existing natural gas grids for transporting SNG could pose a risk to the energy transition if as a result the necessary repurposing of methane pipelines for hydrogen is delayed.** In view of their critical importance, the emphasis in Germany should be on conversion to and construction of hydrogen pipelines. The creation of new CO_2 infrastructure should focus on no-regret CCS applications.

Analysis by TUHH / IUE

Basic SNG supply concept with a nearly closed carbon cycle

Concept for the SNG supply chain with nearly closed carbon cycle



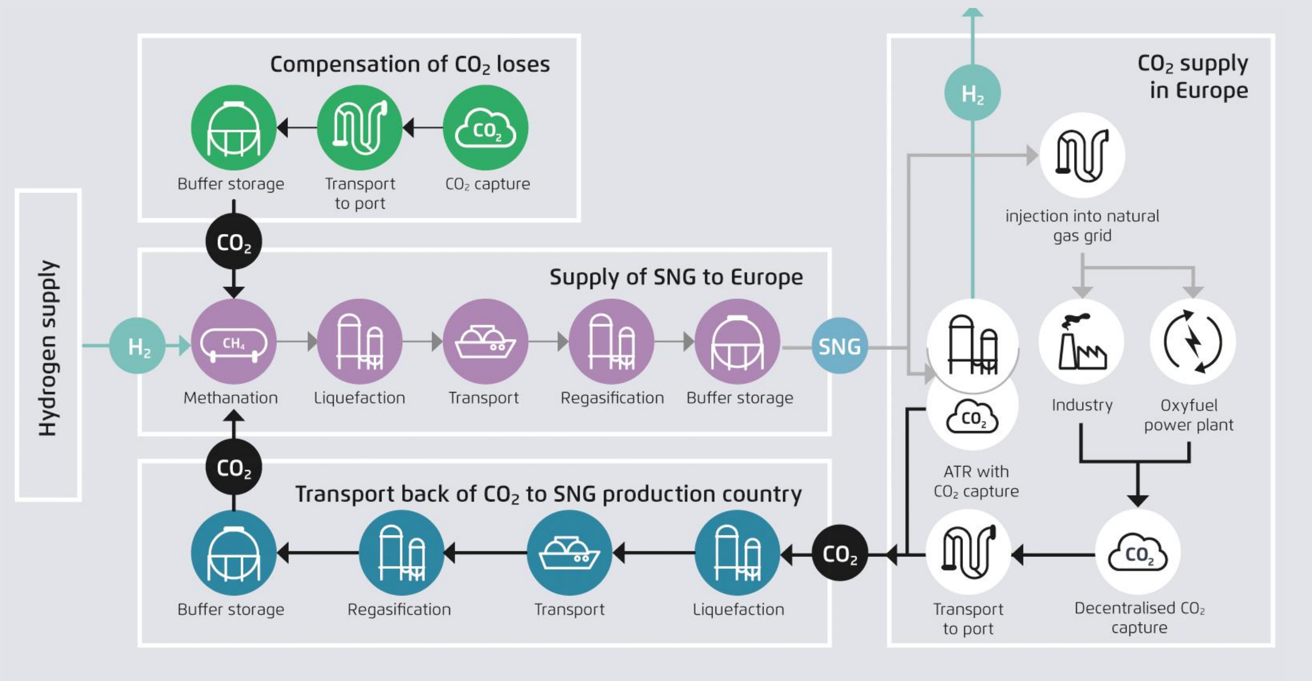
CO_2 = Carbon dioxide, SNG = Synthetic natural gas

TUHH (2023)

- Germany will most likely need to import “green” molecules to reach climate-neutrality.
- Often discussed shipping options include liquefied hydrogen, ammonia, liquid organic hydrogen carriers and methanol.
- SNG supply with a nearly closed carbon cycle has been proposed as an alternative concept.
- It combines the production of renewable (“green”) hydrogen with methanation.
- The resulting SNG is shipped and can be received in LNG terminals.
- If SNG is used in an industrial environment, the CO_2 can be captured and then be transported back to the export country.

SNG supply with a nearly closed carbon cycle includes a range of different technology components

Components of the SNG supply chain with a nearly closed carbon cycle



CO_2 = Carbon dioxide, H_2 = Hydrogen, O_2 = Oxygen, SNG = Synthetic natural gas, ATR = Autothermal reforming

TUHH (2023)

For SNG use in an industrial environment, three different options are of particular interest:

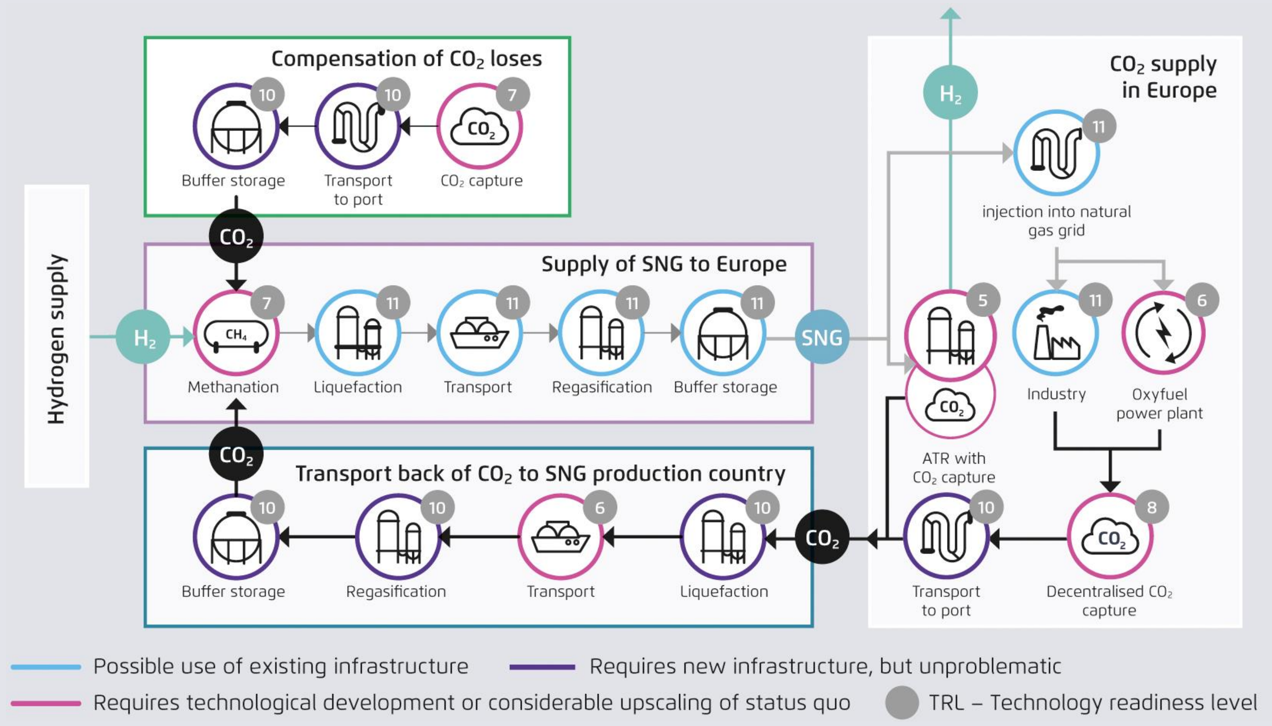
1. Hydrogen supply via Autothermal Reforming (ATR)
2. Power generation by burning SNG in oxyfuel power plants
3. Delivery of SNG to industrial processes

→ If the SNG cannot be used in the immediate vicinity of the port, delivery via natural gas grid and reverse transport of the CO_2 is required.

→ Compensating for carbon losses in SNG supply and carbon cycle requires supply of additional sustainable CO_2 (e.g. via Direct Air Capture).

SNG with a nearly closed carbon cycle as a hydrogen carrier

Components of the SNG supply chain with nearly closed carbon cycle and TRLs



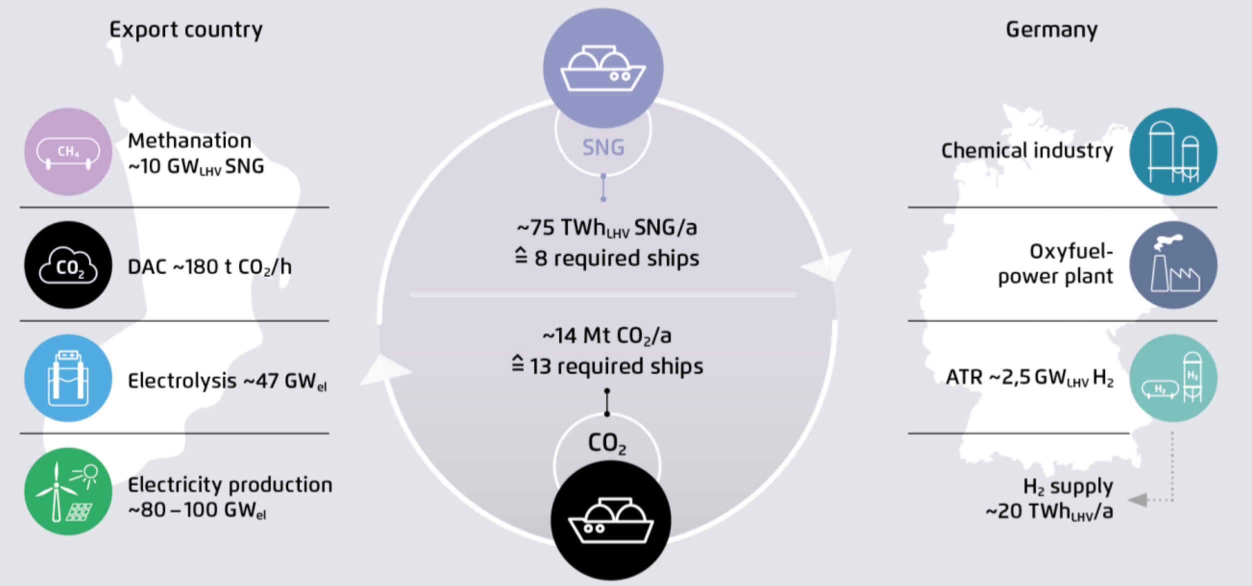
TUHH (2023): CO_2 = Carbon dioxide, H_2 = Hydrogen, O_2 = Oxygen, SNG = Synthetic natural gas, ATR = Autothermal reforming.

- → TRLs of supply chain components vary considerably.
- → Only some components (marked in *blue*) can rely on existing infrastructure:
  - LNG terminals and LNG tanker
  - Potentially; existing natural gas infrastructure for delivering SNG to oxyfuel power plants and industrial sites
- → All other components likely need to construct new assets or infrastructure.
- → Storage and pipelines for SNG and CO_2 as well as liquefaction and regasification of gases could be built without problems (*purple*)
- → Some components (marked in *pink*) need technological development or considerable upscaling, and potentially remaining challenges cannot be finally evaluated here

TRLs are based on the IEA's ETP Clean Energy Technology Guide. Important TRLs: 4–6: Prototype; 7–8: Demonstration; 9: Commercial operation in relevant environment

Supplying 75 TWh of SNG per year to Germany would have considerable infrastructure requirements

Infrastructural dimensions for an exemplary SNG-based hydrogen supply chain



CO_2 = Carbon dioxide, SNG = Synthetic natural gas, ATR = Autothermal reforming, DAC = Direct air capture, LHV = Lower heating value

TUHH (2023)

Number of ships needed:

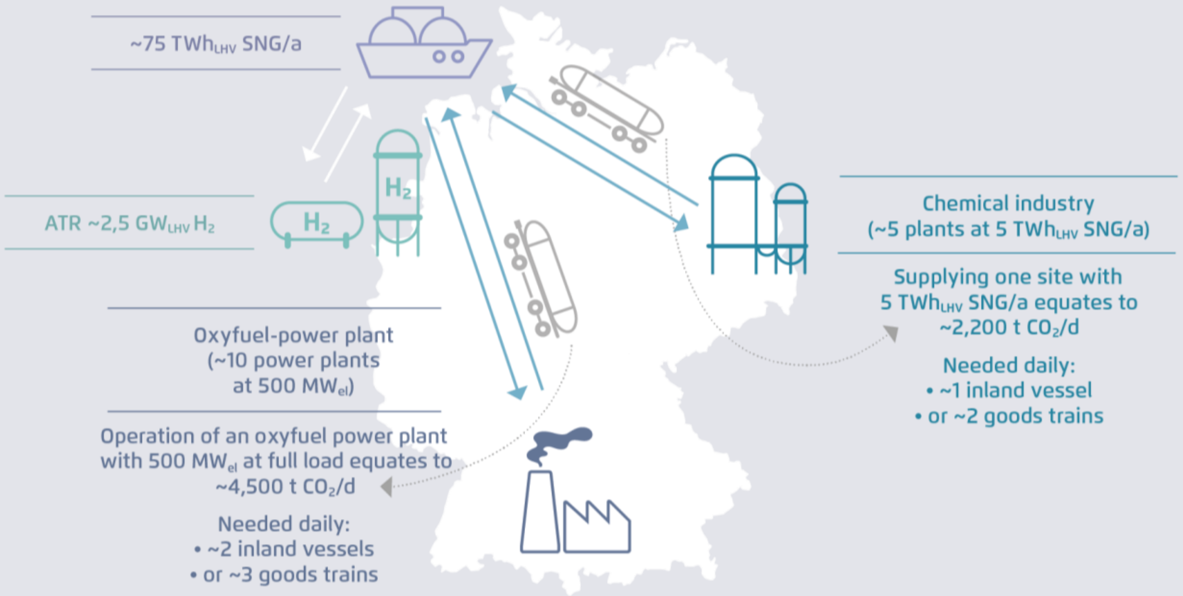
- → 8 for SNG (at average capacity of LNG fleet currently operating)
- → 13 for CO_2 (at largest concept discussed so far in the literature)

Assumptions:

- → Shipping distance of 10 500 km
- → 1/3 of SNG for hydrogen supply via ATR
- → 1/3 for power generation via oxyfuel plants
- → 1/3 for supply of industrial sites
- → CO_2 capture rates: 94% at ATR, 100% at oxyfuel plant, 80% at industrial sites
- → Full load hours (h/a): 3000 for electrolysis, 8000 for ATR & methanation, 2500 for oxyfuel

Using the SNG decentrally would imply transporting CO_2 back to the port

Transport needs in Germany for bringing the CO_2 back to the port (example)



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TUHH (2023)

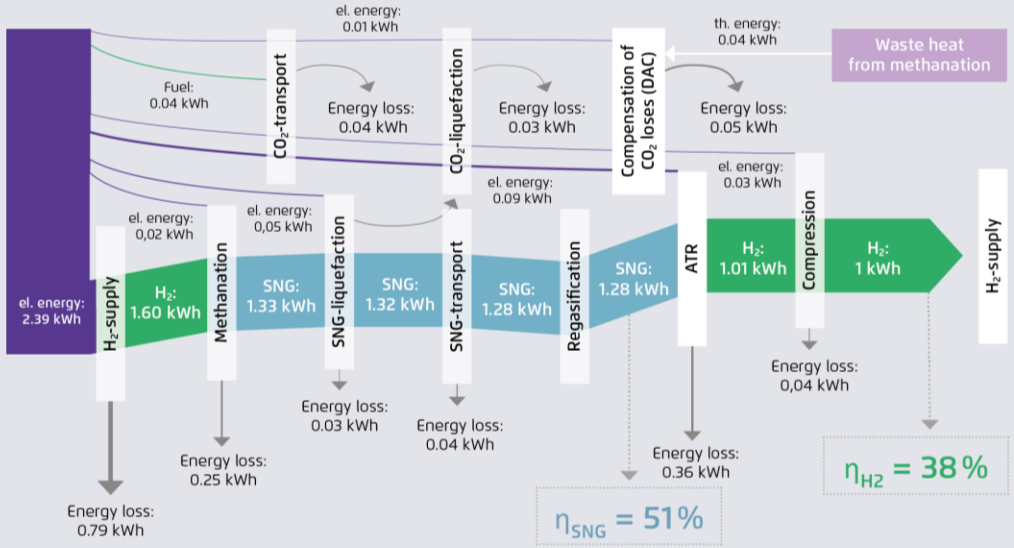
- → Available options for inland CO_2 transport: truck trailers, tank wagons, barges, pipelines
- → CO_2 pipeline not considered here because deemed not available before 2030

CO_2 transport requirements:

- → Operating a 500 MW oxyfuel power plant under full load would require ~2 inland vessels or ~3 goods trains per day
- → Operating an industrial site with an SNG demand of 5 TWh per year would require ~1 inland vessel or ~2 goods trains per day

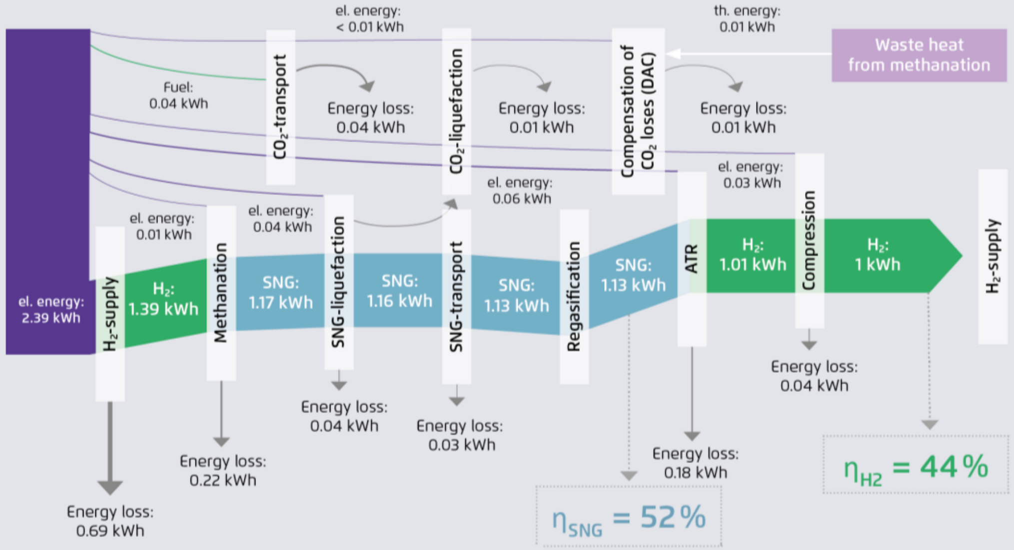
Energy required for an SNG-based hydrogen supply with nearly closed carbon cycle based on …

…data from available literature



(ATR = Autothermal reforming, CO_2 = Carbon dioxide, DAC = Direct air capture, el. energy = electrical energy, H_2 = Hydrogen, SNG = Synthetic natural gas, th. energy = thermal energy)

… data from the industry



(ATR = Autothermal reforming, CO_2 = Carbon dioxide, DAC = Direct air capture, el. energy = electrical energy, H_2 = Hydrogen, SNG = Synthetic natural gas, th. energy = thermal energy)

TUHH (2023). All values are based on the lower heating value (LHV) and are rounded to decimal places.
*Transport distance 10,500 km

How does the SNG concept compare with other hydrogen import options?

Specific energy use and energy efficiency for H_2 supply in Wilhelmshaven for different import options

CGH_2 = Compressed gaseous hydrogen, CH_3OH = Methanol, DAC = Direct air capture, H_2 = Hydrogen, LH_2 = Liquid hydrogen, LHV = Lower heating value, LOHC = Liquid organic hydrogen carrier, NH_3 = Ammonia, recirc. = Recirculation, SNG = Synthetic natural gas, WHV = Wilhelmshaven

TUHH (2023). All calculated values relate to the lower heating value (LHV) and reflect transport distances of 10 500 km (ship) and 660 km (pipeline), as well as hydrogen supply at 100 bar.

- → H_2 supply via pipeline from neighbouring countries (e.g. Norway) is by far the most efficient system (66%) as no conversion losses occur.
- → Among the shipping options, liquid H_2 is the most efficient (52%) as there is little overall loss thanks to the lack of chemical conversion.
- → If H_2 is bound to (in the case of LOHC) or converted into a carrier (SNG, NH_3, CH_3OH), additional conversion losses occur.
- → SNG with a nearly closed CO_2 cycle has a similar efficiency to NH_3 (incl. cracking) and LOHC with the use of external heat.
- → SNG with CO_2 supplied only via Direct Air Capture (DAC) has the lowest efficiency of all analysed H_2 import options.

Efficiency is the main cost-driver for all H_2 supply chains …

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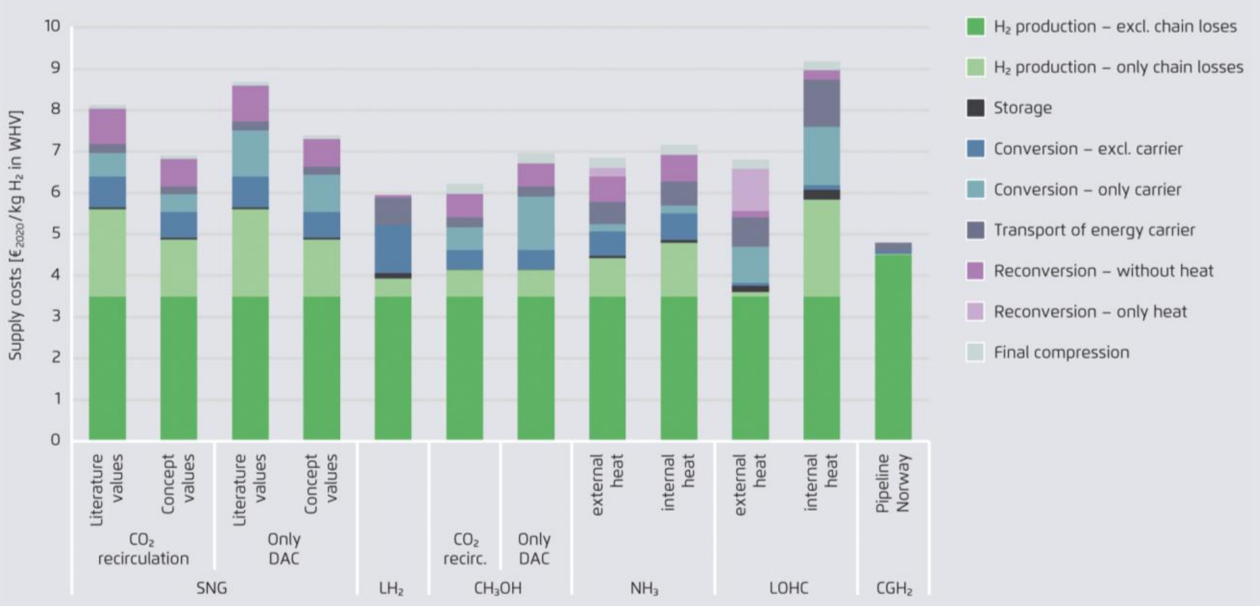
Specific costs for H_2 supply in Wilhelmshaven for different import options



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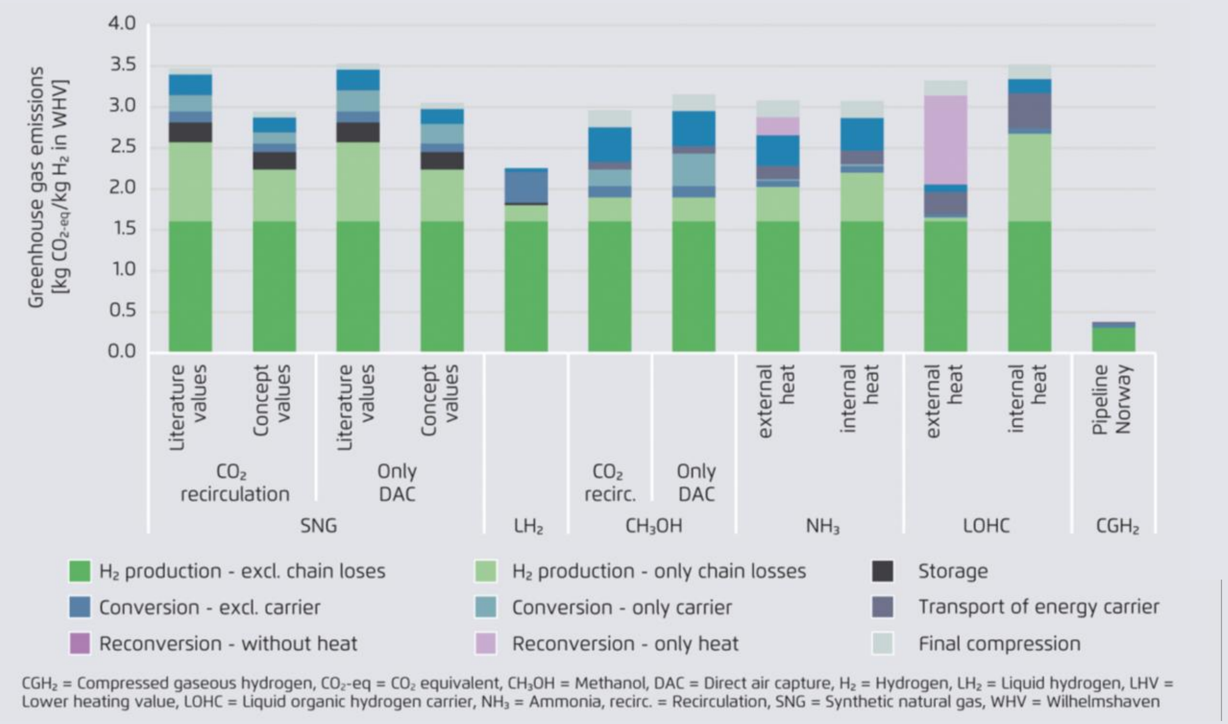
TUHH (2023). All calculated values reflect transport distances of 10 500 km (ship) and 660 km (pipeline), as well as hydrogen supply at 100 bar.

- → In the analyzed case H_2 supply via pipeline from Norway shows 20% lower cost compared to the most economic shipping option (liq. H_2).
- → This is possible even with H_2 production in Norway based on offshore wind having higher costs (4.50 €/kg H_2) than H_2 production from onshore wind and PV (3.50 €/kg H_2).
- → In the case of SNG-based H_2 supply, an extra cost arises primarily from high conversion energy losses, which needs to be offset by additional H_2 production.
- → Existing infrastructure as ships and LNG terminals may represent a minor share of the total H_2 supply cost of an SNG-based concept.
- → Locally available waste heat at the destination site can considerably reduce the H_2 delivery costs, particularly for LOHC.

… and for the greenhouse gas emissions as well

Specific greenhouse gas emissions of hydrogen supply in Wilhelmshaven for different import options

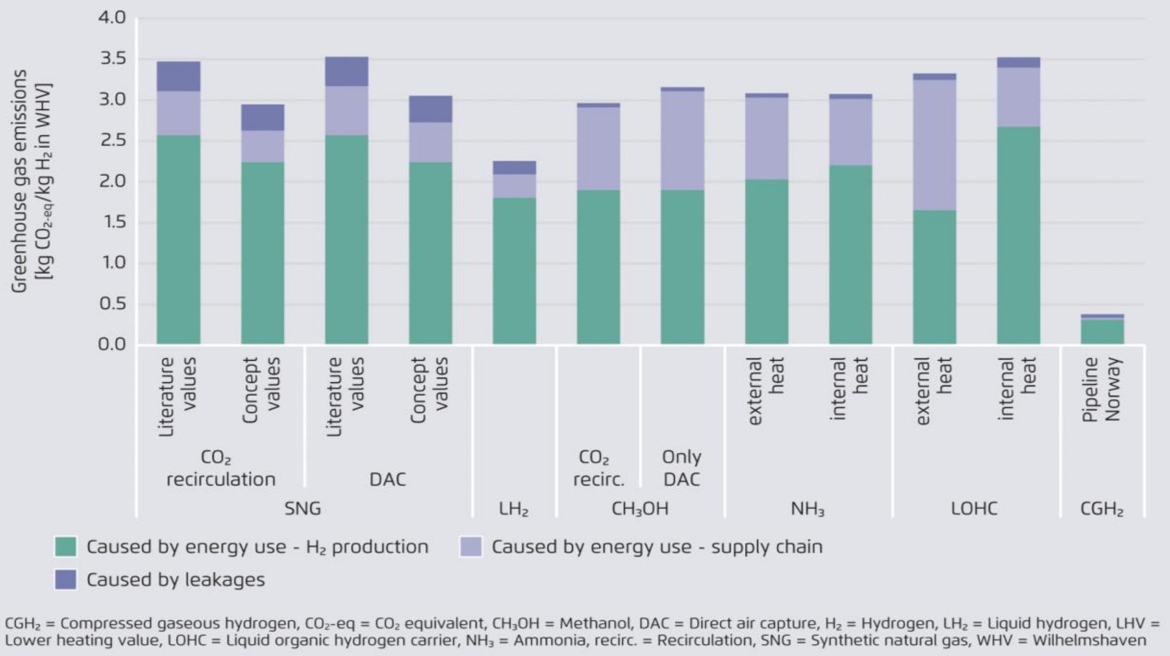


TUHH (2023). All calculated values reflect transport distances of 10 500 km (ship) and 660 km (pipeline), as well as hydrogen supply at 100 bar.

- However, the source of renewable energy also plays a role since offshore wind from Norway has a lower emission factor (6 CO_{2-eq}/kWh_{el}) than the assumed hybrid systems on the Arabian Peninsula region which are dominated by solar PV (32 CO_{2-eq}/kWh_{el}).
- Fewer conversion steps also make H_2 supply via pipelines even less intensive in GHG emissions compared with shipping options.
- The source of waste heat used to de-hydrogenate LOHC plays an important role in the GHG emissions of the supply chain.

GHG emissions: methane versus hydrogen leakage

Specific greenhouse gas emissions of hydrogen supply in Wilhelmshaven for different import options

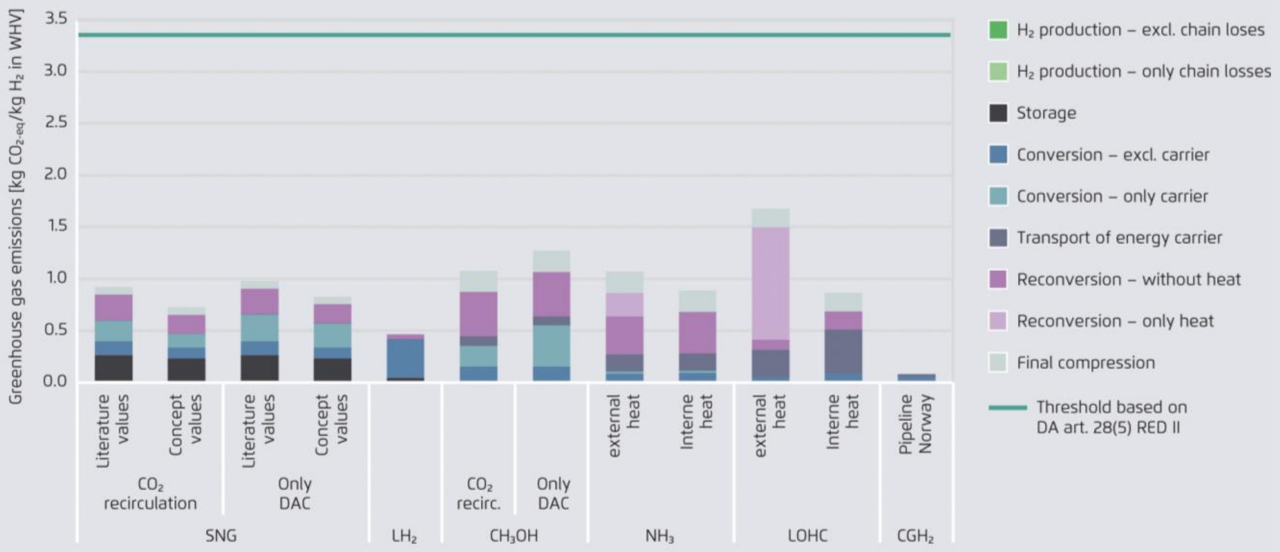


TUHH (2023). All calculated values reflect transport distances of 10 500 km (ship) and 660 km (pipeline), as well as hydrogen supply at 100 bar.

- → The majority of GHG emissions always result from the supply of energy for hydrogen production.
- → Leakages in the form of methane (CH_4) may represent important sources of GHG emissions for the H_2 supply chain based on SNG with nearly closed CO_2 cycle.
- → These emissions will require compensation via carbon capture and storage (CCS) to make the SNG concept climate-neutral.
- → As an indirect GHG, H_2 leakages during production, storage and transport show a negligible climate impact on the other H_2 supply chains.
- → CO_2 leakages from the SNG concept are not considered since these emissions would need to be compensated with DAC anyway to maintain the energy flow.

The EU criteria for Renewable Fuels of Non-Biological Origin (RFNBO) exclude embodied CO_2 emissions from renewable energy generation

Specific greenhouse gas emissions of hydrogen supply in Wilhelmshaven for different import options – without embodied emissions from renewables



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TUHH (2023). All calculated values reflect transport distances of 10 500 km (ship) and 660 km (pipeline), as well as hydrogen supply at 100 bar.

- → The adopted EU criteria establish a greenhouse gas emissions limit for RFNBOs at 3.38 kg $CO_{2\text{-eq}}$/kg H_2. In this legal framework, the emissions of renewable energy generation (from plant manufacturing) are not considered.
- → All analysed H_2 supply chains would be clearly below this emissions limit and therefore compliant with the existing EU regulations, including the SNG concept.

Agora Industry
Anna-Louisa-Karsch-Str. 2
10178 Berlin
www.agora-industry.org

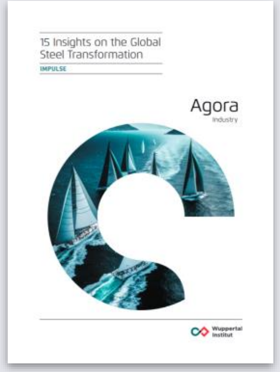
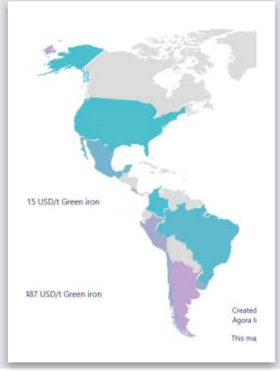
Agora Energiewende
Anna-Louisa-Karsch-Str. 2
10178 Berlin
www.agora-energiewende.de

Contact

leandro.janke@agora-industrie.de

fabian.carels@tuhh.de

Publications on hydrogen and industry

Hydrogen import options for Germany	15 Insights on the global steel transformation	Business opportunity analyser for Power-to-X products	12 Insights on hydrogen	Making renewable hydrogen cost-competitive
				
> analysis (DE)	> impulse (EN)	> interactive tool (EN)	> impulse (EN) > impulse (DE)	> main study > legal analysis
> summary (EN) > slide deck (EN)	> webinar (EN)	> data documentation (EN)	> webinar (EN)	> slide deck > webinar