GHG EMISSION FACTORS AND CONVERSION EFFICIENCIES FOR MAKING RFNBO GHG EMISSION CALCULATIONS

RFNBO Greenhouse Gas Emissions

GHG emission factors and conversion efficiencies for making RFNBO GHG emission calculations

An Expertise for Rijksdienst voor Ondernemend (RVO) Nederland

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ludwig bölkow systemtechnik

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R E P O R T

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TABLES

ACRONYMS AND ABBREVIATIONS

ASU	Air separation plant
CGH_2	Compressed gaseous hydrogen
CH_3OH	Methanol
CH_4	Methane
CO_2	Carbon dioxide
DA	Delegated Act
DAC	Direct air capture
GHG	Greenhouse Gas
GWP	Global warming potential
H_2	Hydrogen
HFO	Heavy fuel oil
LBST	Ludwig-Bölkow-Systemtechnik
LCA	Life cycle analysis
LH_2	Liquefied hydrogen
LHV	Lower heating value
LN_2	Liquefied nitrogen
LSFO	Low sulphur fuel oil
N_2	Nitrogen
NH_3	Ammonia
N_2O	Nitrous oxide
ORC	Organic Rankine cycle
PEM	Proton exchange membrane
PSA	Pressure swing adsorption
RED	Renewable Energy Directive
RFNBO	Renewable Fuel of Non-Biological Origin
yr	Year

1 INTRODUCTION

Both the European Commission as well as EU Member States have ambitious goals for the production and use of green hydrogen, which is hydrogen produced through electrolysis using renewable electricity.

As part of the current revision of the recast of the Renewable Energy Directive (RED-II), the European Council and Parliament discuss binding RFNBO targets for transport and for the industry. RFNBO is the abbreviation for ‘Renewable Fuels of Non-Biological Origin’, which is renewable hydrogen or other energy carriers (such as ammonia or methanol) produced from renewable hydrogen.

On May 20th, the European Commission published two relevant delegated acts. One (the Delegated Act to RED-II article 27.3 or ‘DA 27.3’) sets rules on when electricity input into an electrolyser can be considered to be ‘additional’, the second (the ‘DA 28.5’) proposes a methodology for the calculation of GHG emissions from RFNBO’s. Both delegated acts are still drafts, a four-week consultation period recently ended. The final versions of the DA’s should be published late 2022.

For companies that want to produce and/or import RFNBO’s, not only these two delegated acts are important, but also other RED-II requirements on RFNBO’s which are ‘mass balance' (art. 30.1) and ‘70% GHG reduction’ (art. 25.2, to be moved to art. 29(a) when RED-II is to be revised). Companies seek for investor certainty and they therefore want to understand the implications of these requirements.

2 OBJECTIVE

The study aims to present input/output data and efficiencies of processes required for making GHG calculations on the following RFNBO production pathways:

1. H_2 production, H_2 compression, H_2 transport by pipeline or tube trailer, CGH_2 refueling station, H_2 use

2. H_2 production, H_2 liquefaction LH_2 transport by ship, evaporation at import terminal, transport via pipeline, CGH_2 refueling station, H_2 use

2b. H_2 production, H_2 liquefaction, LH_2 transport by ship, transport via LH_2 trailer, evaporation at CGH_2 refueling station, H_2 use

3a. H_2 and N_2 production, NH_3 synthesis, NH_3 transport by ship (sea), NH_3 transport by ship (river)/pipeline/truck, NH_3 use

3b. H_2 and N_2 production, NH_3 synthesis, NH_3 transport by ship (sea), NH_3 cracking, H_2 compression, H_2 transport by pipeline or tube trailer, H_2 use

4. H_2 production, methanol synthesis using CO_2 from direct air capture (DAC) as carbon source, methanol transport by ship (sea), methanol transport via train and truck.

In this report some example GHG calculations are made, using the emission data for some specific fuels as shown in chapter 3.9. Please note that – when making full life cycle assessment (LCA) calculations following the methodology as described in (a Delegated Act under) the recast Renewable Energy Directive – also emissions due to the provision of fuels shall be taken into account. These provisions are for instance the emissions due to crude oil winning, transport, and oil refining.

3 LIST OF INPUT/OUTPUT DATA AND EFFICIENCIES

3.1 H_2 production via water electrolysis

Table 1 shows the input and output data for alkaline electrolysers from selected manufacturers, Table 2 shows the input and output data for electrolysers where proton exchange membranes (PEM) are used as electrolyte.

Table 1: Input and output data for alkaline electrolysers from selected manufacturers

	Unit	Cummins 2021a	Nel 2021	Sunfire 2022	Thyssenkrupp 2019	Average
Per MJ of H_2						
Input						
Electricity	MJ/MJ_{H2}	1.726	1.534	1.567	1.667	1.623
Water	kg/MJ_{H2}	0.074	0.074	0.074	0.074	0.074
Output						
H_2	MJ	1	1	1	1	1
O_2	kg/MJ_{H2}	0.066	0.066	0.066	0.066	0.066
Efficiency (LHV)		58.0%	65.2%	63.8%	60.0%	61.6%
Pressure H_2	10^5 Pa	10	2	31	1.3	
Per kg of H_2						
Input						
Electricity	MJ/kg	207	184	188	200	195
Water	kg/kg	8.94	8.94	8.94	8.94	8.94
Output						
H_2	kg	1	1	1	1	1
O_2	kg/kg	7.94	7.94	7.94	7.94	7.94

Table 2: Input and output data for PEM electrolysers from selected manufacturers

	Unit	Cummins 2021b	Nel 2021l	Siemens 2022	ITM 2022	Average
Per MJ of H_2						
Input						
Electricity	MJ/MJ_{H2}	1.530	1.667	1.5656	1.6672	1.608
Water	kg/MJ_{H2}	0.074	0.074	0.074	0.074	0.074
Output						
H_2	MJ	1	1	1	1	1
O_2	kg/MJ_{H2}	0.066	0.066	0.066	0.066	0.066
Efficiency (LHV)		65.3%	60.0%	63.9%	60.0%	62.2%
Pressure H_2	10^5 Pa	30	31	1.1	31	
Per kg of H_2						
Input						
Electricity	MJ/kg	184	200	188	200	193
Water	kg/kg	8.94	8.94	8.94	8.94	8.94
Output						
H_2	kg	1	1	1	1	1
O_2	kg/kg	7.94	7.94	7.94	7.94	7.94

There are some hydrogen losses during operation and maintenance of electrolysis plants. Hydrogen losses occur from leakages through casing and pipework, venting during start-up and shutdown (0.05 to 0.6%), venting of oxygen containing hydrogen from crossover (0.05 to 0.15%), and purging processes to remove impurities (3-10%). The hydrogen losses can be reduced by re-routing the vented and purged gases and oxidation to water by passing them over recombining catalysts [Frazer-Nash 2022] or sending the sending these gases to a flare.

There is a huge bandwidth for the hydrogen losses and emissions indicated in literature. [Arrigoni et al. 2022] indicates a hydrogen release into atmosphere of only about 0.2% of the generated hydrogen for today and 0.03% for 2030 citing a presentation from Air Liquide. [Frazer-Nash 2022] indicated far higher hydrogen release to atmosphere of up to 9.2% for today which can be decreased to 0.24 to 0.52% by applying best available technology.

Table 3 shows the hydrogen emissions from hydrogen production via water electrolysis with venting and purging to atmosphere and with full recombination of H_2 from purging and crossover venting.

Table 3: H_2 emissions from H_2 production via water electrolysis

		Frazer-Nash 2022		Arrigoni et al. 2022	
		50% confidence level	99% confidence level	Today	2030
With venting and purging to atmosphere:					
H_2 loss		3.32%	9.20%	0.20%	
	$g/MJ_{H2, LHV}$	0.286	0.845	0.0167	
With full recombination of H_2 from purging and crossover venting:					
H_2 loss		0.24%	0.52%		0.030%
	$g/MJ_{H2, LHV}$	0.020	0.044		0.0025

3.2 LH_2 liquefaction

Table 4 shows the electricity consumption and hydrogen losses for large-scale hydrogen liquefaction based on data from [IDEALHY 2013] for the operation at 100% and 50% of maximum capacity compared with an existing H_2 liquefaction plant with a capacity of 5 t LH_2 per day in Leuna in Germany described in [Haberstroh 2019]. The maximum capacity of the H_2 liquefaction plant in [IDEALHY 2013] amounts to about 50 t of LH_2 per day and unit.

Table 4: Electricity consumption and H_2 loss from H_2 liquefaction

	Unit	100% load	100% load	50% load
Capacity	t LH_2/d	5	50	50
	$MW_{LH2, LHV}$	6.9	69	69
Electricity consumption	MJ/MJ_{LH2}	0.357	0.203	0.233
	MJ/kg_{LH2}	42.82	24.34	28.01
	kWh/kg_{LH2}	11.90	6.76	7.78
H_2 loss		Up to 9.5%*	1.625%	1.625%
	$g/MJ_{H2, LHV}$	0.875	0.138	0.138

*[Haberstroh 2019]: single digit percentage, [Arrigoni et al. 2022]: 10% including transfer operations to LH_2 trailer.

3.3 NH_3 and methanol synthesis

The NH_3 synthesis typically is carried out at 10 to 25 MPa and a temperature of 400 to 500°C according to the following reaction:

$$1.5\ H_2 + 0.5\ N_2 \rightarrow NH_3$$

The reaction is exothermal. The excess steam is used for steam turbines used for compression. The NH_3 synthesis plant data shown in Table 5 includes the net electricity requirement for H_2 and N_2 compression, and the electricity for the air separation plant (ASU) to provide pure N_2.

Direct methanol synthesis using CO_2 and H_2 as feedstock is carried out at a pressure of about 8 MPa and a temperature of 240 to 270°C according to the following reaction:

$CO_2 + 3 H_2$ --> $CH_3OH + H_2O$

The reaction is exothermal.

The methanol synthesis plant data shown in Table 5 includes H_2 and CO_2 compression from 3.0 MPa (H_2) or 0.1 MPa (CO_2) to 7.8 MPa, methanol synthesis, methanol purification, an organic Rankine cycle (ORC) plant for electricity generation, and steam generation from purge gases [Van-Dal and Bouallou 2013].

Table 5: NH_3 and methanol synthesis

Parameter	Unit	NH_3 synthesis	Methanol synthesis	Comment
Capacity (NH_3 or CH_3OH)	t/h	83.3	59.3	
Pressure H_2 feed	10^5 Pa	30	30	
Pressure CO_2 feed	10^5 Pa	-	1	
Pressure synthesis	10^5 Pa	100-250	78	
Per MJ of NH_3				
Input				
H_2	$MJ/MJ_{NH3\ or\ CH3OH}$	1.149	1.228	178 kg/t_{NH3}
CO_2	$kg/MJ_{NH3\ or\ CH3OH}$	-	0.0745	88 t per 59.3 t of methanol
Electricity	$MJ/MJ_{NH3\ or\ CH3OH}$	0.163*	0.0538	1.73 MWh/t_{NH3}
N_2 from air	$kg/MJ_{NH3\ or\ CH3OH}$	0.0442	-	
Output				
NH_3, methanol	MJ	1	1	
Heat	$MJ/MJ_{NH3\ or\ CH3OH}$	0	0.0863	No excess heat for NH_3
Efficiency of conversion		87.0%	81.4%	
CO_2 emissions	$g/MJ_{NH3\ or\ CH3OH}$	0	5.53	From excess CO_2
Per kg of NH_3 or CH_3OH				
Input				
H_2	$MJ/kg_{NH3\ or\ CH3OH}$	21.35	24.48	
CO_2	$kg/kg_{NH3\ or\ CH3OH}$	-	1.48	
Electricity	$MJ/kg_{NH3\ or\ CH3OH}$	3.04*	1.074	For NH_3 incl. ASU
N_2 from air	$kg/kg_{NH3\ or\ CH3OH}$	0.822	-	
Output				
NH_3, methanol	kg	1	1	
Heat	$MJ/kg_{NH3\ or\ CH3OH}$	0	1.72	
Data source		DECHEMA 2017	[Van-Dal & Bouallou 2013]	

*Adjusted to the higher efficiency of electric driven compressors compared to steam turbine driven compressors (see text below)

In literature a range of numbers can be found for electricity consumption for NH_3 and methanol synthesis, the numbers in Table 5 give an example from one literature source. Report [Ortiz Cebolla et al. 2022] gives in paragraphs 2.3.1 and 2.4.1 an indication of the magnitude of this range (1.2 to 2.7 GJ/t of NH_3, an outlier giving a value of 5 GJ/t of NH_3, and 0.63 to 5.4 GJ/t of methanol).

The electricity requirement strongly depends on the pressure of the feed gases and the pressure required for NH_3 synthesis. E. g. if a low-pressure electrolyser operated nearly ambient pressure is used the feed hydrogen pressure will be about 0.1 MPa leading to a higher electricity consumption than if a pressurised electrolyser is applied.

If high-pressure NH_3 synthesis (30 to 46 MPa) is applied the electricity requirement is higher than in case of a low-pressure absorbent-enhanced NH_3 synthesis (1 to 3 MPa). However, the technology readiness level (TRL) for the absorbent-enhanced NH_3 synthesis is low (4-5) [Rouwenhorst et al. 2019].

For the 2.7 GJ/t of NH_3 [Smith et al. 2020] has been cited in [Ortiz Cebolla et al. 2022] where an electrolysis plant operated at 1 MPa combined with high-pressure Haber-Bosch synthesis process operated at 15 MPa has been assumed. The separation of the NH3 has been carried out via condensation at -25 to -33°C and a pressure of about 14 MPa.

[Rouwenhorst et al. 2019] cited in [Ortiz Cebolla et al. 2022] indicates an electricity consumption for the synthesis loop of 0.112 to 1.712 kWh per kg of NH_3 or about 0.403 to 6.163 GJ per t of NH_3. The ASU consumes about 0.25 kWh per kg of NH_3 or about 0.9 GJ per t of NH_3 leading to 1.30 to 7.06 GJ of electricity per t of NH_3. The electricity consumption data refer to small-scale NH_3 synthesis plant using ruthenium-based catalysts instead of iron-based catalysts used in NH_3 synthesis plants today (reason: less poisoning through O_2 leading to lower H_2 purity requirement). Low-pressure (1 to 3 MPa) absorbent-enhanced NH_3 synthesis is applied.

[Liu et al. 2020] cited in [Ortiz Cebolla et al. 2022] indicate am electricity consumption for the NH_3 synthesis loop of 1.165 GJ per t of NH_3 and 0.480 MJ per t of NH_3 for N_2 production if cryogenic distillation for N_2 separation is assumed leading to about 1.65 MJ per t of NH_3. The NH_3 synthesis is carried out at 20 MPa.

The 5 GJ/t of NH_3 indicated as 'outlier' in [Ortiz Cebolla et al. 2022] citing [DECHEMA 2017] refer to the electricity requirement for compressors (1.4 MWh/t of NH_3) for a hydrogen feed pressure of 3 MPa (the N_2 feed pressure may be lower). Additionally, 0.33 MWh of electricity per t of NH_3 are required for the air separation unit (ASU) leading to 1.73 MWh of electricity per t of NH_3 leading to the 6.23 GJ of electricity per t of NH_3 in Table 5 (the deviation from the sum of the values indicated in GJ are from rounding errors). [DECHEMA 2017] has derived the electricity consumption for the compressors from conventional steam turbine powered compressors without taking into account the higher efficiency of electric motor driven compressors. If the efficiency of the steam turbines is assumed to be 33% and the efficiency of the electric motors to be 90% the electricity consumption for the compressors will be about 0.51 MWh per t of NH_3 (1.4*0.33/0.90 MWh per t of NH_3 = 0.513 MWh per t of NH_3). Then the overall electricity consumption for the NH_3 synthesis step will be about 3.04 GJ per t of NH_3.

[DNV-GL 2016] cited in [Ortiz Cebolla et al. 2022] for the electricity consumption for the methanol synthesis loop refers to methanol from biomass. For methanol from biomass the electricity requirement is indicated with 2.1 MWh per t of methanol or 7.56 GJ pr t of methanol which also includes auxiliary electricity for the operation of the biomass gasification plant.

[Pérez-Fortes et al. 2016] cited in [Ortiz Cebolla et al. 2022] indicates a net electricity consumption (after subtraction of electricity supplied by the ORC turbine) of about 0.170 MWh per t of methanol or about 0.61 GJ per t of methanol. It has been assumed that the CO_2 is derived from flue gas from a coal fuelled power plant. [Pérez-Fortes & Tzimas2016] indicate a net electricity consumption of 0.177 MWh per t of methanol or about 0.64 GJ per t of methanol.

[Nieminen et al. 2019] cited in [Ortiz Cebolla et al. 2022] indicate an electricity consumption of 0.624 MWh per t of methanol or about 2.25 MJ per t of methanol for the gas-phase methanol synthesis process. For the liquid-phase methanol synthesis process the electricity requirement is close to that of the gas-phase process (0,625 to 0.683 MWh per t of methanol) but external heat input is required. The gas-phase methanol synthesis process does not need external heat because the reaction heat is sufficient to supply all process heating.

Swiss Liquid Future, a developer of power-to-methanol plants indicates an electricity consumption of 1 MWh per t of methanol (3.6 GJ per t of methanol) for a hydrogen feed gas pressure of 0.16 MPa. The capacity amounts to 0.5 t of methanol/h for the smaller plant and 10 t of methanol/h for the larger plant [Swiss Liquid Future 2020]. The pressure of the hydrogen feed in [Van-Dal & Bouallou 2013] is assumed to be 3 MPa leading to a net electricity consumption of 1.074 GJ per t of methanol. The capacity amounts to 59.3 t of methanol/h.

Table 5 does not include the supply of CO_2 for methanol synthesis. Table 6 shows the input and output data for the CO_2 supply for methanol synthesis via direct air capture (DAC) based on data from [Climeworks 2017] (electricity and heat demand), [Wurzbacher 2015], and [Wurzbacher 2017] (water extraction from air). The amount of water extracted from air depends on the water content of the air.

Table 6: Direct air capture of CO_2 (DAC)

Parameter	Value	Comment
Input		
Electricity	1.35 MJ/kg_{CO2}	0.30 to 045 kWh/kg_{CO2}
Heat (100°C)	6.36 MJ/kg_{CO2}	1.5 to 2.0 kWh/kg_{CO2}
Output		
CO_2	1 kg	
Water	>1 kg/kg_{CO2}	Depending on the water content of the air

3.4 NH_3 cracker

NH_3 cracking is at an early stage of development. For large-scale NH_3 cracking plants there are only concepts. Most commercially available NH_3 crackers have a capacity of 1 to 2 t H_2/day. These commercial units produce forming gas (a mixture of H_2 and N_2) and rarely include downstream processes for H_2 purification.

The heat demand is met by combustion of hydrogen and unreacted NH_3. The large-scale NH_3 cracking plant (200 t H_2/day) described in [Jackson et al. 2019] includes hydrogen storage with a maximum pressure of 25 MPa. The unreacted NH_3 leaving the NH_3 cracker is removed from the product gas stream via a scrubbing process. The H_2/N_2 mixture is separated via cryogenic gas separation.

Table 7: NH_3 cracking plant

Parameter	Unit	Value	Reference/ comment
NH_3 input	MJ/MJ_{H2}	1.251	NH_3 input: 2734 GWh/yr Output pure H_2: 2186 GWh/yr
Electricity input	MJ/MJ_{H2}	0.145	Electricity input: 316 GWh/yr Output pure H_2: 2186 GWh/yr
Efficiency of conversion	-	80.0%	LHV (H_2 stream)/(LHV (NH_3 stream)

The hydrogen storage provides sufficient pressure for a downstream H_2 pipeline. As a result, no initial hydrogen compression is required. For trailer refuelling also less electricity is required.

3.5 Transport efficiencies

3.5.1 Marine LH_2 transport

The marine transport of hydrogen is carried out via LH_2 carriers which are similar as LNG carriers. Until now, only one very small (transport capacity 1250 m^3 LH_2) prototype LH_2 carrier exists (Suiso Frontier built by Kawasaki) which is not representative for future LH_2

transport. Kawasaki's future LH_2 carrier will have a transport capacity of 140,000 m^3 of LH_2 [Kamiya et al. 2014]. The vaporized LH_2 is used as fuel for ship propulsion. In future the fuel demand probably is fully met by H_2.

Table 8 shows the transport efficiency for maritime LH_2 transport for different transport distances. The LH_2 tanks must not be filled to 100%. Furthermore, the LH_2 tanks must not be completely emptied to keep the LH_2 tanks cold.

Table 8: Maritime LH_2 transport via LH_2 carrier

Parameter	Unit	2500 km	5000 km	Reference
Transport capacity	m^3	160,000	160,000	Kamiya et al. 2014
Filling ratio		85%	85%	
Heel		5%	5%	
Net payload	t LH_2	9160	9160	
Distance (one way)	km	2500	5000	
Speed	knots	16	16	Kamiya et al. 2014
	km/h	30	30	
Boil-off rate		0.20%/day	0.20%/day	Kamiya et al. 2014
		1.4%/roundtrip	2.8%/roundtrip	
Fuel consumption (one way)	kWh/(t_{LH2} km)	0.181	0.181	Hank et al. 2020
	kWh/km	1658	1658	
Fuel consumption	kWh/roundtrip	8,290,000	16,580,000	
Share boil-off		52%	52%	
Share supplemental fuel (additional LH_2)		48%	48%	
LH_2 delivered	t	8912	8663	
LH_2 input including H_2 for ship propulsion	MJ/MJ	1.0279	1.0574	
Transport efficiency		97.3	94.6%	

Table 9: Import terminal

Parameter	Unit	Value	Reference
Ship unloading			
Capacity	m^3/h	10,000	Kolff 2021 p. 85
	t/h	709	
Pump power	kW	385	Kolff 2021 p. 85
	MJ_e/MJ_{LH2}	0.0000163	
	MJ_e/kg_{LH2}	0.00195	
Evaporation (Re-gasification via super ORV using seawater as heat source)			
Electricity	kJ/kg_{H2}	224	Kolff 2021 p. 87
	MJ_e/MJ_{H2}	0.0018673	
	MJ_e/kg_{LH2}	0.224	
Pressure	10^5 Pa	50	Kolff 2021 p. 140
Import terminal total			
Electricity	MJ_e/MJ_{H2}	0.0018835	
	MJ_e/kg_{LH2}	0.2260	

If the hydrogen should be transported as LH_2 the re-gasification step has to skipped.

3.5.2 Marine NH_3 and methanol transport

Marine transport of NH_3 generally is carried out with fully refrigerated LPG carriers. NH_3 carriers are similar as LPG carriers. Most LPG carries also can transport NH_3. The largest NH_3 carriers have a transport capacity of about 50,000 t of NH_3.

Table 10 shows the assumptions and results for the marine transport of NH_3 with fully refrigerated NH_3 carriers.

Table 10: Marine NH_3 transport (5000 km as example)

Parameter	Unit	Value	Reference/ comment
Deadweight, summer draught	t	56146	Sum of cargo, fuel, fresh water, ballast water. provisions, passengers, and crew
Capacities			
Cargo (4 x IMO Type A tanks)	m^3	84017	ICE 2018
HFO	m^3	3728	
Marine diesel oil	m^3	436	
Lubrication oil	m^3	140	
Fresh water	m^3	555	
Crew	persons	31	
Payload NH_3	t	51475	Calculation from numbers above
Utilization		50%	Return voyage empty
Service speed	knots	16.5	ICE 2018
	km/h	30.6	
Cruising range	nautical miles	21,000	ICE 2018
	km	38,892	
HFO consumption	kg/km	95.6	
	MJ/km	3781	
Marine diesel oil	kg/km	9.6	
	MJ/km	404	
Fuel consumption total	MJ/km	4185	
Distance	km	5000	Assumed as example
Fuel consumption total including return voyage	$MJ/(t_{NH3}$ km)	0.163	
	MJ/kg_{NH3}	0.815	
	MJ/MJ_{NH3}	0.0438	
Fuel type	-	LSFO	To calculate the CO_2 emissions
CO_2 emissions	$g/(t_{NH3}$ km)	13.2	If LSFO is used as fuel
	g/kg_{NH3}	66.1	
	g/kg_{NH3}	3.55	

Marine transport of methanol is carried out via methanol carriers. One of the largest methanol carriers is the methanol carrier Millennium Explorer which has a cargo capacity of about 120,000 m^3 of methanol (~95,000 t of methanol) [Wärtsilä 2015]. Although the Millennium Explorer has already been built in 1999 it is still one of the largest methanol carriers. Table 11 shows the assumptions and results for marine methanol transport.

Table 11: Marine methanol transport (5000 km as example)

Parameter	Unit	Value	Reference/ comment
Payload methanol	t	100,000	O´Connor 2002
Speed	knots	15	O´Connor 2002
	km/h	27.8	
Distance	km	5000	Assumed as example
Fuel consumption incl. return voyage (empty)	Btu/(t_{CH3OH} nautical mile)	104	O´Connor 2002
	MJ/(t_{CH3OH} km)	0.0592	
	MJ/kg_{CH3OH}	0.296	
	MJ/MJ_{CH3OH}	0.0149	
Fuel type	-	LSFO	
CO_2 emissions	g/(t_{CH3OH} km)	4.81	
	g/MJ_{CH3OH}	1.21	

3.5.3 Long-distance H_2 pipeline

Before injection of the hydrogen into a long-distance pipeline, compression from the pressure of the H_2 production plant to the pressure of the pipeline is required (initial H_2 compression). Electrically driven compressors are assumed for initial hydrogen compression. The pressure of the long-distance pipeline typically is about 8.5 MPa [NEA 2022]. The electricity consumption presented in Table 12 has been calculated based on the equation in chapter 3.8. Table 12 shows the assumptions and results for initial hydrogen compression.

Table 12: Initial H_2 compression for injection into long-distance pipeline

Parameter	Unit	Value	Comment/ reference
Number of stages	-	2	
Adiabatic exponent	-	1.402	
T (in)	K	313	Temperature of H_2 leaving the electrolyser
T (intercooling)	K	333	
Suction pressure	10^5 Pa	25	e. g. pressure of the electrolysis plant
Final pressure	10^5 Pa	85	[NEA 2022]
Compression ratio per stage	-	1.8	
z @ suction pressure	-	1.0255	
z @ final pressure		1.0900	
Compression work	J/mol	3800	
Efficiency compressor		80%	
Efficiency electric motor		90%	
Electricity consumption	kWh_e/Nm^3	0.0654	
	kWh_e/kg	0.73	
	MJ_e/kg	2.62	
	MJ_e/MJ_{LHV}	0.0218	

In case of land-based long-distance pipelines typically there is a compressor every 200 km. In case of a submarine pipeline the layout is different, e. g. a larger pipeline diameter for the same transport capacity to avoid compressors.

The energy requirement for re-compression depends on the pressure drop which depends on the roughness of the pipeline, pressure, the pipeline diameter, and the hydrogen throughput. The pressure drop Δp can be calculated by:

$$\Delta p = \left(p_{in}^2 - \lambda \cdot \frac{16}{\pi^2} \cdot \rho_0 \cdot p_0 \cdot \frac{T}{T_0} \cdot l \cdot z \cdot \dot{V}^2 \cdot \frac{1}{d^5}\right)^{0.5}$$

where:

p_{in} Input pressure of the pipeline in Pa

λ Pipe friction number

ρ_0 Density of the hydrogen at standard conditions (0.1013 MPa, 273.15 K)

p_0 Standard pressure: 101300 Pa

T Temperature of the pipeline

T_0 Standard temperature: 273.15 K

l Pipeline length in m

z compressibility factor

$\dot{V}$ Hydrogen flow in Nm³/s

d Pipeline diameter in m

The pipe friction number λ can be calculated by:

$$\lambda = \frac{1}{\left(2 \cdot \log_{10}\left(\frac{d}{k_i}\right) + 1.14\right)^2}$$

where:

d pipeline diameter

k_i Roughness pipeline in mm in mm

Table 13 shows the energy efficiency of hydrogen transport via long-distance pipeline for a typical long-distance pipeline layout for a distance of 1000 km.

Table 13: Long-distance H_2 pipeline (1000 km as example)

Parameter	Unit	Value	Comment/ reference
Layout long-distance pipeline			
H_2 input	Nm^3/h	3,600,000	[NEA 2022]
	kg/s	89.995	
	GW_{LHV}	10.80	
Pipeline diameter	mm	1000	[NEA 2022]
Pressure (p_{in})	10^5 Pa	85	
Distance	km	1000	
Distance between compressor stations	km	200	
Pressure drop			
Density (H_2)	kg/Nm^3	0.090	
Compressibility factor z (p_{in})	-	1.090	
Compressibility factor z (p_{out})	-	1.068	
Compressibility factor (average)	-	1.079	
Roughness ki	mm	0.02	New gas pipelines
Pipe friction number λ	-	0.009005	
Temperature	K	288	
Velocity (p_{in})	m/s	15.2	
Pressure drop per stage	10^5 Pa	20.2	
Compressor station			
Number of stages	-	1	
Adiabatic exponent	-	1.402	
T (in)	K	288	T (pipeline)
T (intercooling)	K	333	
Suction pressure	10^5 Pa	64.8	
Final pressure	10^5 Pa	85.0	
Compression ratio per stage	-	1.31	
z @ suction pressure	-	1.07	
z @ final pressure		1.09	
Compression work	J/mol	730	
Efficiency compressor	-	80%	
Efficiency gas turbine	-	33%	
H_2 input compressor	kWh/Nm^3_{H2}	0.0343	
	$MW_{H2,\ LHV}$	123	
H_2 output after 1^{st} re-compression	$GW_{H2,\ LHV}$	10.67	
Energy related H_2 input per compressor station	MJ/MJ	1.01156	
Energy efficiency H_2 transport			
Number of compressor stations	-	5	
Energy related H_2 input H_2 transport total	MJ/MJ	1.0592	1.01157^5
Efficiency H_2 transport	-	94.4%	$1/(1.01157^5)$

3.5.4 H_2 distribution via pipeline

For hydrogen distribution via regional trunk pipeline electrically driven compressors have been assumed.

Regional hydrogen pipelines often do not contain compressors along the way. Compression from the pressure of the H_2 production plant to the pressure of the pipeline is required, the energy input therefore depends on the pressure in the pipeline system (e. g. 10 and 7.5 MPa in the Air Liquide pipeline in Belgium/France/The Netherlands and 5 MPa entrance pressure in the Gasunie pipeline system to be constructed in The Netherlands with connections to Belgium and Germany [Air Liquide & Gasunie 2022]).

Table 14: Regional trunk H_2 pipeline (400 km as example)

Parameter	Unit	Value	Comment/ reference
Layout regional trunk H_2 pipeline			
H_2 input	Nm^3/h	300,000	
	kg/s	7.49	
	MW_{LHV}	900	
Pipeline diameter	mm	600	
Pressure (p_{in})	10^5 Pa	30	
Distance	km	400	
Distance between compressor stations	km	200	
Pressure drop			
Density (H_2)	kg/Nm^3	0.090	
Compressibility factor z (p_{in})	-	1.03	
Compressibility factor z (p_{out})	-	1.03	
Compressibility factor (average)	-	1.03	
Roughness ki	mm	0.02	New gas pipelines
Pipe friction number λ	-	0.010	
Temperature	K	288	
Velocity (p_{in})	m/s	10.0	
Pressure drop per stage	10^5 Pa	0.090	
Compressor stations			
Number of stages	-	1	
Adiabatic exponent	-	1.402	
T (in)	K	288	T (pipeline)
T (intercooling)	K	333	
Suction pressure	10^5 Pa	24.9	
Final pressure	10^5 Pa	30.0	
Compression ratio per stage	-	1.21	
z @ suction pressure	-	1.03	
z @ final pressure		1.03	
Compression work	J/mol	472	
Efficiency compressor	-	80%	
Efficiency electric motor	-	90%	

Parameter	Unit	Value	Comment/ reference
Electricity consumption per compressor station	kWh_e/Nm^3_{H2}	0.0081	
Number of compressor stations	-	2	
Electricity consumption compressor stations	kWh_e/Nm^3_{H2}	0.0163	
	kWh_e/kg_{H2}	0.18	
	MJ_e/kg_{H2}	0.651	
	MJ_e/MJ_{H2}	0.0054	
H_2 loss		0.48%	[Frazer-Nash 2022]

For the local hydrogen distribution to the refuelling stations no compressors are required. The pressure drop is low. However, there are some hydrogen losses in the local hydrogen distribution too leading to the overall hydrogen losses in the pipeline grid as shown in Table 15.

Table 15: H_2 losses in H_2 pipeline grids

	Unit	Gasunie 2022	Frazer-Nash 2022	Arrigoni et al. 2022	
			99% confidence level	Today	2030
Regional trunk pipeline:					
H_2 loss		0.010%	0.48%		
	$g/MJ_{H2,\,LHV}$*	0.0008	0.0404		
Local pipeline:					
H_2 loss			0.53%		
	$g/MJ_{H2,\,LHV}$*		0.0444		
Total:					
H_2 loss			1.01%	1.20%	0.70%
	$g/MJ_{H2,\,LHV}$*		0.0848	0.1012	0.0588

*Related to the H_2 delivered to a local H_2 consumer

[Arrigoni et al. 2022] indicates a hydrogen loss of 1.2% for today and 0.7% for 2030 citing a presentation from Air Liquide. The sum of hydrogen losses for the 'National transmission system' and the 'distribution network' in UK indicated in [Frazer-Nash 2022] for a 99% confidence level leads to similar results (~1%). [Gasunie 2022] indicates are rather low value for the hydrogen losses for the planned hydrogen pipeline grid in the Netherlands.

3.5.5 H_2 distribution via tube trailer

The hydrogen leaves the water electrolysis plant at a pressure of between 0.13 and 31 MPa. For trailer refuelling the hydrogen has to be compressed to about 25% above the maximum pressure of the tube trailer (Table 16). Table 17 shows the energy requirement and associated GHG emissions for the transport of hydrogen via tube trailer.

Table 16: Compressor for tube trailer refuelling

Parameter	Unit	1	2	3	4	5
Maximum pressure tube trailer	10^5 Pa	248	345	300	500	200
Number of stages	-	3	3	3	3	3
Adiabatic exponent	-	1.402	1.402	1.402	1.402	1.402
T (in)	K	313	313	313	313	313
T (intercooling)	K	333	333	333	333	333
Suction pressure	10^5 Pa	25	25	25	25	25
Final pressure	10^5 Pa	310	431	375	625	250
Compression ratio per stage	-	2.3	2.6	2.5	2.9	2.2
z @ suction pressure	-	1.0255	1.0255	1.0255	1.0255	1.0255
z @ final pressure	-	1.3319	1.4622	1.4018	1.6705	1.2674
Compression work	J/mol	9102	11045	10176	13783	8011
Efficiency compressor	-	80%	80%	80%	80%	80%
Efficiency electric motor	-	90%	90%	90%	90%	90%
Electricity consumption	kWh_e/Nm^3_{H2}	0.1568	0.1902	0.1753	0.2374	0.1380
	kWh_e/kg_{H2}	1.74	2.11	1.95	2.64	1.53
	MJ_e/kg_{H2}	6.27	7.61	7.01	9.50	5.52
	MJ_e/MJ_{H2}	0.0523	0.0634	0.0584	0.0792	0.0460

Table 17: H_2 transport via tube trailer/bundles of pressure vessels (150 km as example)

Parameter	Unit	Quantum 2022	Quantum 2022	Calvera 2021	Hexagon 2020	M-Tech 2020		
Model		VPLite-H45/40′	VP5000-H		Purus	9 elements	18 elements	18 elements
Length CGH_2 trailer	ft	40	45		45	18	18	36
Maximum pressure	10^5 Pa	248	348	300	500	200	200	200
Gross transport capacity	kg H_2	803	1195	960	1400	155	315	630
Net transport capacity*	kg H_2	720	1099	874	1312	136	276	552
Distance (one way)	km	150	150	150	150	150	150	150
Distance (roundtrip)	km	300	300	300	300	300	300	300
Diesel consumption	l/100 km	30.5	30.5	30.5	30.5	25.0	25.0	30.5
	MJ/km	11.0	11.0	11.0	11.0	9.0	9.0	11.0
	MJ/MJ_{H2}	0.0381	0.0249	0.0313	0.0209	0.1653	0.0813	0.0496
	MJ/kg_{H2}	4.57	2.99	3.76	2.50	19.82	9.75	5.96
	$MJ/(t_{H2}$ km)	30.4	19.9	25.1	16.7	132.2	65.0	39.7
Emissions								
CO_2	g/km	802	802	802	802	657	657	802
	g/MJ_{H2}	2.8	1.8	2.3	1.5	12.1	6.0	3.6
	g/kg_{H2}	334	219	275	183	1452	715	436
	$g/(t_{H2}$ km)	2230	1460	1835	1223	9681	4763	2908
CH_4	g/km	0.034	0.034	0.034	0.034	0.034	0.034	0.034
	g/MJ_{H2}	0.00012	0.00008	0.00010	0.00006	0.00063	0.00031	0.00015
	g/kg_{H2}	0.0142	0.0093	0.0117	0.0078	0.0751	0.0370	0.0185
	$g/(t_{H2}$ km)	0.0945	0.0619	0.0778	0.0518	0.5009	0.2465	0.1232
N_2O	g/km	0.020	0.020	0.020	0.020	0.020	0.020	0.020
	g/MJ_{H2}	0.000069	0.000046	0.000057	0.000038	0.000368	0.000181	0.000091
	g/kg_{H2}	0.00834	0.00546	0.00686	0.00457	0.04420	0.02175	0.01087
	$g/(t_{H2}$ km)	0.0556	0.0364	0.0457	0.0305	0.2946	0.1450	0.0725
CO_2 equivalents**	g/km	809.2	809.2	809.2	809.2	663.9	663.9	809.2
	g/MJ_{H2}	2.8	1.8	2.3	1.5	12.2	6.0	3.7
	g/kg_{H2}	337	221	278	185	1467	722	440
	$g/(t_{H2}$ km)	2249	1472	1851	1233	9781	4813	2933

* At a minimum pressure of 2 MPa; ** based on IPCC AR4

The H_2 losses are low. MAHYTEC indicates a permeation rate of 0.1 Ncm^3 per hour and litre of water volume for its 50 MPa pressure vessels with a water volume of 160 to 300 l and a hydrogen storage capacity of 5.0 to 9.5 kg [MAHYTEC 2021]. For a 50 MPa pressure vessel with a water volume of 300 l and a hydrogen storage capacity of 9.5 kg the hydrogen losses will be 0.00068% per day. As a result, the hydrogen losses via permeation for the transport of CGH_2 via truck can be neglected[1].

3.5.6 H_2 transport & distribution via LH_2 trailer

Table 18 shows the assumptions and results for the transport of hydrogen via LH_2 trailer.

Table 18: H_2 transport via LH_2 trailer (400 km as example)

Parameter	Unit	Value	Reference/ comment
Gross transport capacity	kg LH_2	3500	Filling ratio: 93%
Ullage		5%	LH_2 remaining in the tank
H_2 losses		0.5%	Rough estimate
Net transport capacity	kg H_2	3325	
Distance (one way)	km	400	Assumed as example
Distance (roundtrip)	km	800	
Diesel	l/100 km	30.5	
	MJ/km	11.0	
	MJ/MJ_{H2}	0.0220	
	MJ/kg_{H2}	2.64	
	$MJ/(t_{H2}$ km)	6.59	incl. return voyage (empty)
Emissions			
CO_2	g/km	802	
	g/MJ_{H2}	1.6	
	g/kg_{H2}	193	
	$g/(t_{H2}$ km)	483	incl. return voyage (empty)
CH_4	g/km	0.034	
	g/MJ_{H2}	0.00007	
	g/kg_{H2}	0.00818	
	$g/(t_{H2}$ km)	0.0205	incl. return voyage (empty)
N_2O	g/km	0.020	
	g/MJ_{H2}	0.000040	
	g/kg_{H2}	0.00481	

[1] In [Frazer-Nash 2022] the hydrogen losses have been indicated with 0.24% per day citing the same reference. However, the authors mixed up the unit in g per hour and kg of hydrogen stored indicated in [Bigelow & Michael 2018] with the Ncm^3 per hour and litre of water volume indicated in [MAHYTEC 2021] for the calculation of the daily hydrogen losses.

	$g/(t_{H2}\ km)$	0.0120	incl. return voyage (empty)
H_2	g/MJ_{H2}	0.0419	independent from distance because only from LH_2 transfer
	g/kg_{H2}	5.025	
CO_2 equivalent	g/km	809	w/o H_2 losses
	g/MJ_{H2}	2.09	incl. H_2 losses, independent from distance
	g/kg_{H2}	251	
	$g/(t_{H2}\ km)$	487	incl. return voyage (empty), w/o H_2 losses

In [Frazer-Nash 2022] very high hydrogen losses have been indicated for LH_2 distribution via LH_2 trailer (13.2% for 99% confidence level). The hydrogen losses for LH_2 distribution via LH_2 in [Frazer-Nash 2022] have been derived from the evaporation rate in the LH_2 tank (0.1 to 5% depending on the size and the type of LH_2 storage) which leads to an overestimate of hydrogen losses because dormancy period where no hydrogen loss occur has not been taken into account.

The boil-off gas generation for a 50 m^3 cryogenic tank (approximately the size of the LH_2 tank of a LH_2 trailer) amounts to about 0.4% per day [Ghafri et al. 2022]. At the beginning after finishing the refuelling of the LH_2 tank, the boil-off gas generation leads to a pressure increase in the LH_2 tank without releasing hydrogen into atmosphere until the maximum pressure (1.2 MPa) is reached. When the maximum pressure the pressure valve opens and hydrogen is released. This dormancy period amounts to about 30 days for large 50 m^3 LH_2 tanks mounted on LH_2 trailers [NHEG 1992]. As a result, H_2 losses only occur during transfer of LH_2 from a stationary LH_2 tank to the LH_2 trailer and from the LH_2 trailer to the stationary LH_2 tank at the refuelling station.

In [Arrigoni et al. 2022] the hydrogen losses from the sum of hydrogen liquefaction and LH2 distribution are indicated with ~10% for today and ~2% for 2030 citing a presentation of Air Liquide. Since for hydrogen liquefaction hydrogen losses of about 1.6% have been assumed for LH_2 distribution about 0.5% have been assumed as a rough estimate if best available technology is applied.

3.5.7 NH_3 transport via inland navigation

LPG carriers can generally be used for the transport of NH_3. In [Schifffahrt-online 2009] a typical inland ship for the transport of gases such as LPG and NH_3 (‘LRG Gas 87’) is described. The transport capacity of the 8 pressure vessels of the ‘LRG Gas 87’ amounts to 2831 m^3 of LPG. The mass of NH_3 is higher than that of LPG. The cargo also is mass-limited. Therefore, the same mass related transport capacity as for LPG has to be assumed (density of LPG: 0.504 t/m^3).

The fuel consumption has been scaled from a different inland ship described in [Schiff und Technik 2021]. The typical fuel consumption of a diesel engine with 2*1700 kW amounts to 500 l of diesel/h upstream and 300 l/h downstream the river. Then, the average fuel consumption will be 400 l of diesel/h. The fuel consumption has been scaled to that of the inland ship used in this study for NH_3 transport via the rated power of the main engines (634/1700*400 l/h = 149 l/h).

Table 19 shows the assumptions and results for transport of NH_3 via inland ship.

Table 19: NH_3 transport via inland ship 'NH₃ carrier LRG GAS 87' (500 km as example

Parameter	Unit	Value	Reference/ comment
Payload	m^3 LPG	2831	Schifffahrt-online 2009
	t NH_3	1427	Same as for LPG, see text
Average speed	km/h	15	Upstream: 10 km/; Downstream: 20 km/h
Fuel consumption	l diesel/h	149	Schifffahrt-online 2009; Schiff und Technik 2021
	l diesel/km	9.95	
	MJ diesel/km	354	
Utilisation	-	50%	Return voyage empty
Distance	km	500	Assumed as example
Fuel consumption incl. return voyage	MJ/(t_{NH3} km)	0.5002	
	MJ/kg_{NH3}	0.2501	
	MJ/MJ_{NH3}	0.0135	
CO_2 emissions	g/(t_{NH3} km)	36.6	
	g/kg_{NH3}	18.3	
	g/MJ_{NH3}	0.99	

3.5.8 NH_3 transport via pipeline

Table 20 shows the assumptions and results for the transport of NH_3 via pipeline.

Table 20: NH_3 transport via pipeline

Parameter	Unit	Value	Reference/ comment
Distance between NH_3 pumps	km	100	Goff 2020
Capacity	t/d	7800	Goff 2020
	t/h	325	
Electricity for NH_3 pumping	kW/pump	1200	Goff 2020
Distance	km	400	Assumed as example
Number of pumps	-	4	
Electricity consumption	MJ_e/(t_{NH3} km)	0.1329	
	MJ/kg_{NH3}	0.0532	
	MJ/MJ_{NH3}	0.00286	

3.5.9 NH_3 transport via train

If only the water volume of the NH_3 tank is indicated, the NH_3 payload has to be calculated. NH_3 is a toxic gas. Measures have to be taken to avoid any NH_3 release. The density of NH_3 changes with temperature.

The 'International. Safety Guide for Inland Navigation Tank-barges and Terminals' [ISGINTT 2010] describes procedures to avoid overfilling of containers. The maximum loading limit (LL) to which a cargo tank may be loaded is determined by the following formula:

$$LL = FL \cdot \frac{\rho R}{\rho L}$$

where:

FL: filling limit as specified (85% according to [Workforce Safety & Insurance 2003])

ρR relative density of the cargo at the reference temperature (typically 288 K)

ρL relative density of the cargo at the loading temperature and pressure (maximum allowable temperature: 328 K)

Table 21 shows the assumptions and results for the transport of NH_3 via electric train.

Table 21: NH_3 transport via train (400 km as example)

Parameter	Unit	Value	Reference/ comment
Water volume container with nurse tank	m^3	24.5	
Filling limit	-	85%	Workforce Safety & Insurance 2003
Density pressurized NH_3 @ 288 K	t/m^3	0.61776	
Density pressurized NH_3 @ 328 K	t/m^3	0.55435	Maximum allowed temperature
Loading limit	-	0.76275	ISGINTT 2010, p. 487
m (NH_3)	t	10.4	
m (container)	t	7.7	
m (NH_3 + container)	t	18.0	Relevant for payload train
Distance	km	400	Assumed as example
Payload train	t	200	GEMIS 2016
Utilisation	-	50%	GEMIS 2016
Electricity consumption inclusive return voyage with empty NH_3 containers	MJ/tkm	0.21	GEMIS 2016
	$MJ_e/(t_{NH3}\ km)$	0.365	
	MJ/kg_{NH3}	0.146	
	MJ/MJ_{NH3}	0.00787	

3.5.10 NH_3 distribution via truck

Table 22 shows the assumptions and results for the transport of NH_3 via truck.

Table 22: NH_3 distribution via truck (150 km as example)

Parameter	Unit	Value	Reference/ comment
Water volume nurse tank	US gal	10000	TRANACAER 2011
	m^3	37.85	
Filling limit	-	85%	Workforce Safety & Insurance 2003
Density pressurized NH_3 @ 288 K	t/m^3	0.61776	
Density pressurized NH_3 @ 328 K	t/m^3	0.55435	Maximum allowed temperature
Loading limit	-	0.76275	ISGINTT 2010, p. 487
Transport capacity	t NH_3	16.0	
Distance (one way)	km	150	Assumed as example
Distance (roundtrip)	km	300	
Fuel consumption (diesel)	l/100 km	30.5	
	MJ/km	11.0	
	$MJ/(t_{NH3}\ km)$	1.369	incl. return voyage
	MJ/kg_{NH3}	0.205	
	MJ/MJ_{NH3}	0.0110	
Emissions			
CO_2	g/km	802	
	$g/(t_{NH3}\ km)$	100	incl. return voyage
	g/kg_{NH3}	15.0	
	g/MJ_{NH3}	0.809	
CH_4	g/km	0.034	
	$g/(t_{NH3}\ km)$	0.00425	incl. return voyage
	g/kg_{NH3}	0.000637	
	g/MJ_{NH3}	0.0000343	
N_2O	g/km	0.020	
	$g/(t_{NH3}\ km)$	0.00250	incl. return voyage
	g/kg_{NH3}	0.000375	
	g/MJ_{NH3}	0.0000202	
CO_2 equivalent*	g/km	809	
	$g/(t_{NH3}\ km)$	101	incl. return voyage
	g/kg_{NH3}	15.2	
	g/MJ_{NH3}	0.816	

*based on IPCC AR4

3.5.11 Methanol transport via train and truck

The maximum payload of a typical rail car (DOT-111 tank car) amounts to about 89.8 t of liquids. The tar weight of chassis with tank amounts to about 29.5 t. The weight of the chassis alone amounts to about 22.7 t leading to a weight for the tank alone of 6.8 t.

Table 23 shows the assumptions and results for the transport of methanol via electric trains.

Table 23: Methanol transport via train (400 km as example)

Parameter	Unit	Value	Reference/ comment
m (methanol)	t	89.8	DOT-111 tank car
m (tank)	t	6.8	DOT-111 tank car
m (methanol + container)	t	96.6	
Distance	km	400	Assumed as example
Payload train (tank + methanol)	t	200	GEMIS 2016
Utilization	-	50%	return voyage with empty tanks
Electricity consumption	MJ_e/tkm	0.21	GEMIS 2016
	$MJ_e/(t_{CH3OH}$ km)	0.226	
	MJ/kg_{CH3OH}	0.0904	
	MJ/MJ_{CH3OH}	0.00453	

Table 24 shows the assumptions and results for the transport of methanol via truck.

Table 24: Methanol transport via truck (400 km as example)

Parameter	Unit	Value	Reference/ comment
Transport capacity	t	26	
Distance (one way)	km	400	Assumed as example
Distance (roundtrip)	km	800	
Fuel consumption (diesel)	l/100 km	30.5	
	MJ/km	11.0	
	$MJ/(t_{CH3OH}$ km)	0.843	incl. return voyage
	MJ/kg_{CH3OH}	0.337	
	MJ/MJ_{CH3OH}	0.0169	
Emissions			
CO_2	g/km	802	
	$g/(t_{CH3OH}$ km)	62	incl. return voyage
	g/kg_{CH3OH}	24.7	
	g/MJ_{CH3OH}	1.24	
CH_4	g/km	0.034	
	$g/(t_{CH3OH}$ km)	0.00262	incl. return voyage
	g/kg_{CH3OH}	0.001046	
	g/MJ_{CH3OH}	0.0000525	
N_2O	g/km	0.020	
	$g/(t_{CH3OH}$ km)	0.00154	incl. return voyage
	g/kg_{CH3OH}	0.000615	
	g/MJ_{CH3OH}	0.0000309	
CO_2 equivalent*	g/km	809	
	$g/(t_{CH3OH}$ km)	62.2	incl. return voyage
	g/kg_{CH3OH}	24.9	
	g/MJ_{CH3OH}	1.25	

*based on IPCC AR4

3.6 Hydrogen storage in salt caverns

According to Gasunie the electricity consumption of hydrogen storage in salt caverns is 0.85 kWh electricity per kg hydrogen stored. This includes electricity for hydrogen compression (major part), as well as electricity for drying, and further electricity use at the hydrogen storage location.

According to [Frazer-Nash 2022] the hydrogen losses amount to about 0.04% (50% confidence level: 0.02%; 99% confidence level: 0.06%). Most of the hydrogen losses come from the surface processing plant such as scheduled shutdown release, component maintenance release, and emergency shutdown release.

Please note that only part of the hydrogen that is fed into a hydrogen distribution pipeline will be stored into salt caverns as to solve short- or long-term mismatch of supply and demand. According to [Gasunie 2022], in 2050 typically 20% of hydrogen that is fed into the distribution pipeline is stored in salt caverns. As in practice it will be impossible to allocate storage emissions to individual users of the hydrogen pipeline distribution system, energy requirements and corresponding GHG emissions from the storage can be attributed to all hydrogen flowing through the pipeline distribution system that includes salt cavern storage by using this factor of 20%.

3.7 H_2 refuelling stations

3.7.1 Refuelling station for H_2 delivery via pipeline

The electricity requirement for hydrogen compression depends on the pressure of the hydrogen delivered by the pipeline and the final pressure(s). Table 25 shows the assumptions and results for a hydrogen refuelling station for the refuelling of 70 MPa vehicle tanks.

Table 25: H_2 refuelling station for H_2 delivery via pipeline

Parameter	Unit	Value	Reference/ comment
Stationary bulk H_2 storage			
Maximum pressure	10^5 Pa	250	Parks et al. 2014, p. 55
Minimum pressure	10^5 Pa	70	Parks et al. 2014, p. 28
Primary compression (loading bulk H_2 storage)			
Number of stages	-	2	Parks et al. 2014, p. 53
Adiabatic exponent	-	1.402	
T (in)	K	288	Temperature of H_2 delivered by pipeline
T (intercooling)	K	333	
Suction pressure	10^5 Pa	30	Pressure of H_2 delivered by pipeline
Final pressure	10^5 Pa	250	

Parameter	Unit	Value	Reference/ comment
Pressure ration per stage	-	2.9	
z @ suction pressure	-	1.0173	
z @ final pressure		1.1663	
Compression work	J/mol	6991	
Efficiency compressor	-	65.0%	Parks et al. 2014, p. 14
Efficiency electric motor	-	90%	
Electricity consumption	kWh_e/Nm^3_{H2}	0.1482	
	MJ_e/MJ_{H2}	0.0494	
Secondary compression (loading high pressure buffer)			
Number of stages	-	2	
Adiabatic exponent	-	1.409	
T (in)	K	288	
T (intercooling)	K	333	
Suction pressure	10^5 Pa	132	
Final pressure	10^5 Pa	880	
Pressure ration per stage	-	2.6	
z @ suction pressure	-	1.0866	
z @ final pressure		1.5928	
Compression work	J/mol	7544	
Efficiency compressor	-	65.0%	Parks et al. 2014, p. 14
Efficiency electric motor	-	90%	
Electricity consumption	kWh_e/Nm^3_{H2}	0.1599	
	MJ_e/MJ_{H2}	0.0533	
H_2 refuelling station total			
H_2 compression	MJ_e/MJ_{H2}	0.1027	
Pre-cooling	MJ_e/MJ_{H2}	0.0405	NREL 2021a (1.35 kWh/kg_{H2})
Total	MJ_e/MJ_{H2}	0.1432	
	MJ_e/kg_{H2}	17.2	
H_2 loss	-	0.25%	Frazer-Nash 2022; MAHYTEC 2021
	$g/MJ_{H2,\ LHV}$	0.0210	Related to the H_2 delivered

3.7.2 Refuelling stations for H_2 delivery via tube trailer

A swap concept is assumed. The tractor truck leaves a full trailer at the refuelling station and takes the empty trailer. The hydrogen is transferred from the tube trailer to the high-pressure buffer storage. At the beginning, the suction pressure for the compressor is the same as the maximum working pressure of the tube trailer. The suction pressure decreases with decreasing filling level of the trailer. It has been assumed that the trailer is emptied until a pressure of 2 MPa is reached.

The average suction pressure for the compressor at the refuelling station can be calculated by:

$$Average\ suction\ pressure = e^{\frac{\ln(p_{min})+\ln(p_{max})}{2}}$$

where

p_{min} Minimum pressure of the tube trailer

p_{max} Maximum working pressure of the tube trailer

Table 26 shows the assumptions and results for hydrogen refuelling stations for H_2 delivery via tube trailer.

Table 26: H_2 refuelling stations for H_2 delivery via tube trailer

Parameter	Unit	1	2	3	4	5	Reference
Maximum pressure tube trailer	10^5 Pa	248	345	300	500	200	
Number of stages	-	4	4	4	4	4	
Adiabatic exponent	-	1.402	1.402	1.402	1.402	1.402	
T (in)	K	288	288	288	288	288	
T (intercooling)	K	333	333	333	333	333	
Average suction pressure	10^5 Pa	70	83	77	100	63	
Final pressure	10^5 Pa	900	900	900	900	900	
Compression ratio per stage	-	1.9	1.8	1.8	1.7	1.9	
z @ suction pressure	-	1.0743	1.0879	1.0819	1.1061	1.0666	
z @ final pressure	-	1.9661	1.9661	1.9661	1.9661	1.9661	
Compression work	J/mol	11367	10613	10931	9778	11864	
Efficiency compressor	-	80%	80%	80%	80%	80%	
Efficiency electric motor	-	90%	90%	90%	90%	90%	
Electricity consumption H_2 compression	kWh_e/Nm^3_{H2}	0.1958	0.1828	0.1883	0.1684	0.2043	
	kWh_e/kg_{H2}	2.18	2.03	2.09	1.87	2.27	
	MJ_e/kg_{H2}	7.83	7.31	7.53	6.74	8.17	
	MJ_e/MJ_{H2}	0.0653	0.0610	0.0628	0.0562	0.0681	
Electricity consumption pre-cooling	kWh_e/Nm^3_{H2}	0.1215	0.1215	0.1215	0.1215	0.1215	
	kWh_e/kg_{H2}	1.35	1.35	1.35	1.35	1.35	NREL 2021a
	MJ_e/kg_{H2}	4.86	4.86	4.86	4.86	4.86	
	MJ_e/MJ_{H2}	0.0405	0.0405	0.0405	0.0405	0.0405	
Electricity consumption total	kWh_e/Nm^3_{H2}	0.317	0.304	0.310	0.290	0.326	
	kWh_e/kg_{H2}	3.53	3.38	3.44	3.22	3.62	
	MJ_e/kg_{H2}	12.69	12.17	12.39	11.60	13.03	
	MJ_e/MJ_{H2}	0.106	0.101	0.103	0.097	0.109	
Hydrogen losses		0.25%	0.25%	025%	0.25%	025%	[Frazer-Nash 2022], [MAHYTEC 2021]

3.7.3 Refuelling station for H_2 delivery via LH_2 trailer

If the hydrogen is dispensed as CGH_2 a high-pressure cryogenic pump will be required. If the hydrogen is dispensed as LH_2 a low-pressure cryogenic pump is required leading to lower electricity consumption.

Table 27: Refuelling station for H_2 delivery via LH_2 trailer

Parameter	Unit	Dispensed as CGH_2	Dispensed as LH_2	Reference/ comment
Electricity consumption	kWh_e/kg_{H2}	1.20	0.01	[Decker 2019b]; Valentin 2001]
	MJ_e/kg_{H2}	4.32	0.04	
	MJ_e/MJ_{H2}	0.0360	0.0003	
H_2 loss	-	0.25%	2%	[Frazer-Nash 2022], [MAHYTEC 2021], [Arrigoni et al. 2022]
	$g/MJ_{H2, LHV}$	0.0210	0.170	Related to the H_2 delivered

[Arrigoni et al. 2022] indicate the hydrogen losses from LH_2 dispensing with 8.5% today and 2% as target for 2020 citing a presentation of Air Liquide. For CGH_2 dispensing the same hydrogen losses as for H_2 delivery via pipeline and CGH_2 trailer is assumed because the LH_2 has to be vaporized in any case to refuel vehicles with CGH_2 tanks.

3.8 Energy requirement for H_2 compression

Generally, the compression ratio per stage should not be more than 3 to 4. Therefore, a multi-stage compressor system is required. To calculate the energy requirement for a multi-stage compressor system the compression ratio for each stage is required. The compression ratio can be calculated by

$$CR = \left(\frac{p_d}{p_s}\right)^{\frac{1}{n}}$$

Where:

CR	Compression rato per stage
p_s	Suction pressure in MPa
p_d	Discharge pressure in MPa
n	Number of compression stages

Then, the compression work can be calculated by

$$W_{comp} = \left\{\frac{\kappa}{\kappa - 1} R \cdot T_s \left[(CR)^{\frac{\kappa-1}{\kappa}} - 1\right] + (n-1)\frac{\kappa}{\kappa - 1} R \cdot T_{IC}\left[(CR)^{\frac{\kappa-1}{\kappa}} - 1\right]\right\} \cdot \frac{z_s + z_d}{2}$$

Where:

W_{comp} Compression work in J per mole of H_2

κ	Isentropic exponent of the gas (H_2: 1.402)
R	Gas constant (8.314 kJ/(mol*K))
T_s	Temperature of the gas at suction pressure in K (assumption: 313 K)
T_{IC}	Temperature of the gas after intercooling in K (assumption: 333 K)
CR	Compression ratio per stage
n	Number of compression stages
z_s	Gas compressibility factor at suction pressure
z_d	Gas compressibility factor at discharge pressure

For the calculation of the electricity requirement the compressor efficiency (assumption: 80%) and the efficiency of the electric motor (assumption: 90%) have to be taken into account. To convert the electricity consumption from J per mole of hydrogen to MJ per Nm^3 of hydrogen the molar volume of hydrogen is required. The molar volume of every gas amounts to about 22.4 l at normal conditions (T = 273.15 K; p = 0.1013 MPa).

Then, the electricity consumption in MJ per Nm^3 of hydrogen for compression can be calculated by

$$W_e = W_{comp} \cdot \frac{1}{\eta_{comp} \cdot \eta_{motor}} \frac{1000\, l/Nm^3}{22.4\, l/mole} \cdot \frac{1}{1000000\, J/MJ}$$

Where:

W_e: Electricity consumption in MJ per Nm^3 of hydrogen

The density of hydrogen amounts to 0.0900 kg per Nm^3 and the lower heating value amounts to 10.80 MJ per Nm^3.

Table 28 shows the electricity requirement for H_2 compression for selected input and output pressures.

Table 28: Electricity requirement for H_2 compression for selected input and output pressures

Input pressure (10^5 Pa)	Output pressure (10^5 Pa)	Compression stages	Electricity requirement (MJ_e/kg_{H2})
1	15	3	5.82
1	20	3	6.55
1	30	3	7.63
1	50	4	8.70
20	50	1	1.95
30	50	1	1.03
30	100	1	2.75
30	150	2	3.67
30	200	2	4.53
30	250	2	5.27
30	300	2	5.93
30	350	2	6.55
30	400	3	6.76
30	450	3	7.26
30	500	3	7.74

This table lists calculated electricity requirement for compression, in practice electricity requirements for compression can be higher or lower depending on compression technology and flow rate. Table 29 shows a comparison of calculated electricity consumption and measured electricity consumption data in [Ortiz Cebolla et al 2022].

Table 29: Comparison of calculated electricity requirement for H_2 compression with actual measured data

Input pressure (10^5 Pa)	Output pressure (10^5 Pa)	Compression stages	Electricity requirement (MJ_e/kg_{H2})		
			Calculated	[Ortiz Cebolla et al. 2022]	
20	100	4	3.4	3.0	Centrifugal
20	500	3	9.0	13.0	Diaphragm
25	450	3	7.8	9.7	Diaphragm
25	450	3	7.8	9.0	Diaphragm
30	450	3	7.3	6.8	Reciprocating
30	450	3	7.3	6.1	Reciprocating
30	450	3	7.3	4.7	Reciprocating
8	500	4	11.5	10.4	Ionic
25	500	4	8.0	7.9	Ionic
6	900	5	16.2	11.9	Ionic
3	900	5	18.9	30.2	Electrochemical
3	950	5	19.4	23.8	Electrochemical
25	1000	4	12.3	15.8	Diaphragm

3.9 GHG emission factors

The global warming potential of the various greenhouse gases is expressed in CO_2 equivalents. Table 30 shows the global warming potential of selected greenhouse gases for a period of 100 years according to the Fourth and Fifth Assessment Reports (AR4 and AR5 respectively) of the Intergovernmental Panel on Climate Change (IPCC).

Table 30: Global warming potentials (GWP) of various greenhouse gases [IPCC 2007], [IPCC 2013], [IPCC 2021]

Greenhouse gas	AR4 (g CO_{2eq}/g)	AR5 (g CO_{2eq}/g)*	AR6 (g CO_{2eq}/g)**	Warwick et al. 2022 (g CO_{2eq}/g)
CO_2	1	1	1	
CH_4 -renewable	25	28	27.0	
CH_4 - fossil	25	30	29.8	
N_2O	298	265*	273	
H_2				11±5

* Table 8.A.1 of the Fifth IPCC Assessment Report; **Table 7.15 of the Sixth IPCC Assessment Report

For the calculation of the greenhouse gases for the utilities shown in Table 31 for the supply of energy carriers such as electricity, natural gas, diesel, and coal the same assumptions as in [JEC 2020] has been applied. For PSA adsorbents the production of zeolite described in

[Fawer et al. 1998] has been used as proxy. For Haber-Bosch NH_3 catalysts the production of Fe_3O_4 nanoparticles described in [Rahman et al. 2022] has been used as proxy.

Table 31: Greenhouse gas emission factors for the provision of utilities

Utility	AR4 (g CO_2eq/kg)	AR5 (g CO_2eq/kg)	AR 6 (g CO_2eq/kg)
Tap water	0.2	0.2	0.2
LN_2	209	209	209
PSA adsorbent for gas cleaning	2474	2486	2486
Haber-Bosch NH_3 catalysts	6374	6368	6379

3.10 Fuel properties

Table 32 shows selected fuel properties assumed for the calculation of energy related input and output data and efficiencies.

Calculation on emissions in this report only serve as an example. The CO_2 emissions taken into account in the table below are only the combustion emissions. When making GHG calculations following calculation methodologies under the recast Renewable Energy Directive (under article 28.5 and under Annexes V.C and VI.B) also emissions due to the provision must be added, which are for instance emissions due the winning, transport, and refining of fossil fuel. In case of fossil diesel, the upstream GHG emissions amount to about 21.9 g CO_2 equivalent per MJ of diesel leading GHG emissions of 95.1 g CO_2 equivalent including combustion (but excluding the non-CO_2 tailpipe GHG emissions at the vehicle).

Table 32: Fuel properties

Parameter	Unit	H_2	NH_3	Methanol	Diesel	Marine diesel	LSHFO	Lub. oil
LHV	MJ/kg	119.96	18.59	19.93	43.13	41.94	39.56	36.00
	MJ/Nm³	10.80						
	MJ/l_{liquid}			15.80	35.88	36.07	39.45	31.43
	kWh/kg	33.32	5.16	5.54	11.98	11.65	10.99	10.00
	kWh/Nm³	3.00						
	kWh/l_{liquid}			4.39	9.97	10.02	10.96	8.73
Density	kg/l_{liquid}	0.0709	0.6820	0.7930	0.8320	0.8600	0.9970	0.8730
	kg/Nm³	0.0900						
CO_2	g/MJ	-	-	68.9	73.2	75.6	81.1	77.3
	g/kWh	-	-	248	264	272	292	278

It has to be noted that this table shows the fuel properties including the CO_2 released by combustion (The CO_2 from combustion is used e. g. for the calculation of the carbon balance). The GHG emissions or the supply (upstream) and use (combustion) mainly depend on the feedstock for fuel production and the fuel used for transportation and distribution of the final fuel.

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Company Profile of LBST

Ludwig-Bölkow-Systemtechnik GmbH (LBST) is an expert consultant for sustainable energy and mobility. With our expertise bridging technologies, markets, and policy we support international clients from industry, finance, politics, and non-governmental organisations in strategy, feasibility, and market assessments. International blue-chip companies trust in our reliable judgment.

Our cutting-edge competence is based on four decades of continuous experience, and on our interdisciplinary team of leading experts.

LBST supports its clients with

System & technology studies	Techno-economic assessment; due diligence; energy and infrastructure concepts; feasibility studies;
Policy consulting	Techno-economic assessment; future scenarios and strategies; analysis and support to the development of regulatory frameworks; evaluations;
Strategy consulting	Product portfolio analysis, identifying new products and services; market analysis, decision support, and policy support;
Sustainability consulting	Life cycle and carbon footprint analysis; natural resources assessment (energy, minerals, water); sustainability due diligence;
Coordination	Project management, monitoring and assessment; and
Capacity building	Studies, briefings, expert workshops, trainings.

Particular expertise exists in energy (renewables, energy storage, hydrogen and fuel cells) and mobility (fuels and drives, infrastructure, mobility concepts), with our work in sustainability cutting across all sectors.

A key common denominator of all activities is the rigorous system approach, making sure all relevant elements of a tightly networked system are taken into account, providing our customers with a comprehensive and complete basis for their decisions.

With our deep understanding of developments and technologies and our truly independent advice, we help our clients with sustainable decisions to secure their future.

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