

HyDelta 2

WP3 – Risks, uncertainty, and collaboration in the hydrogen-based value chain

D3.4 – Technical analysis of hydrogen supply chains – factsheets (update 2023)

Status: final

Document summary

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Dissemination level

PU	Public	X
RE	Restricted to <ul style="list-style-type: none"> Project partners including Expert Assessment Group External entity with whom a Non-Disclosure Agreement exists 	

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Executive summary

This document contains an update of the database with the filled-out factsheets about different components of the H2 value chain elements modelled in the HyDelta 1 project.

- The first version of these factsheets can be found here: <https://doi.org/10.5281/zenodo.6469568>
- The different technologies depicted on the factsheets can be found here: <https://doi.org/10.5281/zenodo.6469592>
- The original modelling done that is based on the information from these factsheets can be found here: <https://doi.org/10.5281/zenodo.6514172>

Note: to understand exactly what each parameter refers to (for example, some parameters presented correspond to numbers in a costing model), to find the sources used, and to better contextualize the data, the reader is referred to the accompanying Excel document, to be found in the same repository.

Samenvatting

Dit document bevat een update van de database met ingevulde factsheets over verschillende onderdelen van het H₂-waardeketenmodel dat gemodelleerd is in het HyDelta 1-project.

- De eerste versie van deze factsheets is te vinden op: <https://doi.org/10.5281/zenodo.6469568>
- De verschillende technologieën die op de factsheets worden weergegeven, zijn te vinden op: <https://doi.org/10.5281/zenodo.6469592>
- Het oorspronkelijke modelleren dat is gebaseerd op de informatie uit deze factsheets is te vinden op: <https://doi.org/10.5281/zenodo.6514172>

Let op: om precies te begrijpen waar elke parameter naar verwijst (bijvoorbeeld, sommige gepresenteerde parameters komen overeen met cijfers in een kostmodel), om de gebruikte bronnen te vinden en de gegevens beter te contextualiseren, wordt de lezer verwezen naar het bijbehorende Excel-document, te vinden in dezelfde locatie als dit rapport.

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Overview

HyDelta 1.0													
Tag	Production	Tag	Conversion	Tag	Terminals (export/import)	Tag	Shipping (long haul)	Tag	Pipeline infrastructure	Tag	Storage	Tag	Reconversion
P1	Electrolysis - Alkaline	C1	H2 compression	T1	Terminal - LH2	SH1	Shipping LH2	I1	High pressure pipeline GH2	ST1	CH2 storage - HP vessels	R1	LH2 regasification
P2	Electrolysis - PEM	C2	H2 liquefaction	T2	Terminal - NH3	SH2	Shipping NH3	I2	Compressor station GH2	ST2	CH2 storage - salt caverns	R2	NH3 dissociation
P3	SMR + CCS	C3	NH3 synthesis	T3	Terminal - MeOH	SH3	Shipping MeOH	I3	Cleaning station GH2	ST3	Liquid storage (LH2)	R3	MeOH reforming
P4	ATR + CCS	C4	MeOH synthesis	T4	Terminal - LOHC	SH4	Shipping LOHC			ST4	Liquid storage (NH3)	R4	LOHC dehydrogenation
		C5	LOHC hydrogenation	T5	Terminal - FA	SH5	Shipping FA			ST5	Liquid storage (MeOH)	R5	FA decomposition
		C6	HCOOH synthesis	T6	Terminal - KBH4	SH6	Shipping KBH4			ST6	Liquid storage (LOHC)	R6	KBH4 decomposition (?)
		C7	KBH4 synthesis							ST7	Liquid storage (FA)		
										ST8	Solid storage (KBH4)		

HyDelta 2.0													
Tag	Production	Tag	Conversion	Tag	Terminals (export/import)	Tag	Shipping (long haul)	Tag	Pipeline infrastructure	Tag	Storage	Tag	Reconversion
P1	Electrolysis - Alkaline	C1	H2 compression	T1	Terminal - LH2	SH1	Shipping LH2	I1	High pressure pipeline GH2	ST1	CH2 storage - HP vessels	R1	LH2 regasification
P2	Electrolysis - PEM	C2	H2 liquefaction	T2	Terminal - NH3	SH2	Shipping NH3	I2	Compressor station GH2	ST2	CH2 storage - salt caverns	R2	NH3 dissociation
P3	SMR + CCS	C3	NH3 synthesis	T3	Terminal - MeOH	SH3	Shipping MeOH	I3	Cleaning station GH2	ST3	Liquid storage (LH2)	R3	MeOH reforming
P4	ATR + CCS	C4	MeOH synthesis	T4	Terminal - LOHC	SH4	Shipping LOHC	I4	Decentral pipeline GH2 (lastmile)	ST4	Liquid storage (NH3)	R4	LOHC dehydrogenation
		C5	LOHC hydrogenation	T5	Terminal - FA	SH5	Shipping FA	I5	LH2 Truck	ST5	Liquid storage (MeOH)	R5	FA decomposition
		C6	HCOOH synthesis	T6	Terminal - KBH4	SH6	Shipping KBH4	I6	GH2 Truck	ST6	Liquid storage (LOHC)	R6	KBH4 decomposition (?)
		C7	KBH4 synthesis					I7	GH2 Small Ship	ST7	Liquid storage (FA)		
								I8	HVAC or HVDC	ST8	Solid storage (KBH4)		
								I9	NH3 Truck				
								I10	NH3 Ship (inland)				
								I11	NH3 Train				
								I12	MeOH Truck				
								I13	MeOH Ship				
								I14	MeOH Train				
								I15	LOHC Truck				
								I16	LOHC Ship				
								I17	LOHC Train				

Legend (all colored cells denote sheets that were changed in this version with respect to HyDelta 1)

Validate/control DNV	Add/complete DNV	Develop DNV	TNO
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Generic input

		Properties of various energy carriers										
		Molecule / mixture										
Property	Unit	H2	LH2	SNG (CH4)	NH3	MeOH	HCOOH	DME	NG	Diesel	Gasoline	CO2
Molecular weight	[g/mol]	2	2	16	17	32	~18-19	~170-180	~120-130	44		
Storage density	[kg/m3]	23.65	70.79	450	681	792	Partenie, O. (Octavian): Calculated based on the standard net enthalpy of combustion, taken from Perry's Chem Eng	-0.9	840	740		
Standard density	[kg/m3]	0.084135	Dr. Y.G. Melese: 1 bar, 150c									
HHV (higher heating value)	[MJ/kg] [GJ/t]	141.8			Ir. T.C. Hajonides van der Meulen: -252.87°C	Partenie, O. (Octavian): liquid density at -33degC			52.0	45.6	45.4	
LHV (lower heating value)	[MJ/kg] [GJ/t]	120.0		Partenie, O. (Octavian): liquid density at 20degC					47.0	42.6	42.3	
Volumetric H2 density	[kg H2/M ³ substance]											
LHV	[GJ/m3]	2.8										
LHV	[kWh/kg]	33.330										
H2 equivalent energy stored	[GJ/m3]	2.8		13.5	14.4	11.9	6.4	10.5				
Market value		1250.0	Saric, M. (Marija): Data from Ammonia p	300.0	350	Partenie, O. (Octavian): ~5% of emissions a	Partenie, O. (Octavian): Typical value according to Ref 4	Partenie, O. (Octavian): Typical value according to Ref 4	280.9	1491.0	2162.2	
Market value		10.4		Partenie, O. (Octavian): ~38g CO2 eq / MJ for SMR-based MeOH, according to ref 6					6.0	35.0	51.1	
Combustion emissions		0							2.66	3.09	3.05	
Combustion emissions	[t CO2 / GJ]	0				0.068	0.17	0.066	0.057	0.073	0.072	
Conventional production emissions	[t CO2 / t]	9.00		0.13	1.80	0.76	2.20		0.13	0.62	0.61	
Conventional production emissions	[t CO2 / GJ]	0.075		0.003	0.10	0.04	0.39		0.003	0.015	0.014	
Total CO2 emissions	[t CO2 / GJ]	0.075		0.058	0.097	0.106	0.563	0.066	0.059	0.087	0.086	

P1: Electrolysis - Alkaline

P1: Electrolysis - Alkaline												
Parameter name	Description	Unit	Source ID	2020	2020	2020	2030	2030	2030	2040	2040	2040
				Low	Mid	High	Low	Mid	High	Low	Mid	High
				Anchor_AEL	Scale of the electrolyzer plant	[MW]			100			100
	System energy efficiency	[%]	(1-3)		64			70			72	
	Reduction of efficiency	[%/y]			1.1%			1.1%			1.1%	
PtH2_eff_kg	Specific power consumption	[kWh/kg H2]	(1-3,13)	50.0	52.1	78.0		47.6	55.0	45.0	46.3	
	Heat released	[%]			26			20			18	
	H2 output, hourly	[t/h]			1.9			2.1			2.2	
	Annual utilization	[%]			45			50			65	
	Operating hours	[h/y]			3942			4380			5694	
	H2 output, annual	[kt/y]			7.6			9.2			12.3	
	O2 output, annual	[kt/y]			60.5			73.6			98.4	
CAPEX_AEL	Total direct cost, specific	[€/kW]	(1-4)		780			450			450	
	System cost decline (annual)	[%]						2			2	
	Total direct cost	[M€]	(1-4)		78.0			45.0			45.0	
ScalingFactor_AEL	Scaling factor	N/A			0.9			0.9			0.9	
	Fixed OPEX	[M€/y]			2.0			1.1			1.1	
	Fixed OPEX	[€/kW/y]					10.0	15.0	20.0			
	Var OPEX	[€/kg H2]	12					0.075			0.075	
	System footprint	[m2/kW]			0.0095							

P2: Electrolysis - PEM

P2: Electrolysis - PEM												
Parameter name	Description	Unit	Source ID	Values/estimates								
				2020	2020	2020	2030	2030	2030	2040	2040	2040
				Low	Mid	High	Low	Mid	High	Low	Mid	High
	Scale of the electrolyzer plant	[MW]			20			20			20	
	System energy efficiency	[%]	(1-3)		60			66			70	
	Reduction of efficiency	[%/y]						1.1%			1.1%	
	Specific power consumption	[kWh/kg H ₂]	(1-3,11)	50	55.6	83		50.5		45	47.6	
	Heat released	[%]			30			24			20	
	H ₂ output, hourly	[t/h]			0.4			0.4			0.4	
	Annual utilization	[%]			45			50			65	
	Operating hours	[h/y]			3942			4380			5694	
	H ₂ output, annual	[kt/y]			1.4			1.7			2.3	
	O ₂ output, annual	[kt/y]			11.4			13.9			18.0	
	Total direct cost, specific	[€/kW]	(1-4)		1000			652			481	
	System cost decline (annual)	[%]						4			3	
	Total direct cost	[M€]	(1-4)		20.0			13.0			9.6	
	Scaling factor	N/A			0.9			0.9			0.9	
	Fixed OPEX	[M€/y]			0.5			0.3			0.2	
	Fixed OPEX	[€/kW/y]					10.0	15.0	20.0			
	Var OPEX	[€/kg H ₂]	10					0.075			0.075	
	System footprint	[m ²]										

P3: SMR (steam methane reforming) + CCS (carbon capture and storage)

P3: SMR + CCS												
Parameter name	Description	Unit	Source ID	Values/estimates								
				2020	2020	2020	2030	2030	2030	2040	2040	2040
				Low	Mid	High	Low	Mid	High	Low	Mid	High
	Scale of the SMR +CCS plant	[MW]	1,2	300	300	300	300	300	300	300	300	300
	System energy efficiency	[%]		76	73	69	76	73	69	76	73	69
	Specific power production	[kWh/MJ H2]		0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	Specific NG consumption	MJ NG/MJ H2	1,2	1.31	1.36	1.44	1.31	1.36	1.44	1.31	1.36	1.44
	H2 output, hourly	[t/h]		9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
	Annual utilization	[%]	2	95	95	95	95	95	95	95	95	95
	H2 output, annual	[kt/y]		75	75	75	75	75	75	75	75	75
	CO2 emissions, annual	[kt/y]	1	305	316	79	305	316	79	305	316	79
	Total direct cost, specific	[€/kW]	1,2	1046	984	1328	951	984	1328	778	984	1328
	System cost decline (annual)	[%]					1	0	0	2	0	0
	Total direct cost	[M€]		314	295	398	285	295	398	233	295	398
	Scaling factor	N/A		0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
	Fixed OPEX	[M€/y]		9.8	9.4	11.5	9.0	9.4	11.5	7.2	9.4	11.5
	System footprint	[m2]										

P4: ATR (autothermal reforming) + CCS (carbon capture and storage)

P4: ATR + CCS												
Parameter name	Description	Unit	Source ID	Values/estimates								
				2020	2020	2020	2030	2030	2030	2040	2040	2040
				Low	Mid	High	Low	Mid	High	Low	Mid	High
	Scale of the ATR+CCS plant	[MW]	1	1350	1350	1350	1350	1350	1350	1350	1350	1350
	System energy efficiency	[%]		82	80	80	82	80	80	82	80	80
	Specific power consumption	[kWh/MJ H2]	1,2,3	0.011	0.014	0.014	0.011	0.014	0.014	0.011	0.014	0.014
	Specific NG consumption	[MJ NG/MJ H2]	1,2	1.18	1.20	1.20	1.18	1.20	1.20	1.18	1.20	1.20
	H2 output, hourly	[t/h]		34	34	34	34	34	34	34	34	34
	Annual utilization	[%]	2	92	92	92	92	92	92	92	92	92
	H2 output, annual	[kt/y]		276	276	276	276	276	276	276	276	276
	CO2 emissions, annual	[kt/y]	1	86	88	175	86	88	175	86	88	175
	Total direct cost, specific	[€/kW]	1,2	1201	1300	1400	1201	1300	1400	1201	1300	1400
	System cost decline (annual)	[%]		0	0	0	0	0	0	0	0	0
	Total direct cost	[M€]		1621	1755	1890	1621	1755	1890	1621	1755	1890
	Scaling factor	N/A										
	Fixed OPEX	[M€/y]		49	53	95	49	53	95	49	53	95
	System footprint	[m2]										

C1: H2 Compression

C1: H2 Compression						
Parameter name	Description	Unit	Source ID	Values/estimates		
				2020	2030	2040
	Scale of compressor	[MW]	[2]	0.941		
	Polytropic efficiency	[%]	[1,4, 5]	90%		
	Specific power consumption	[kWh/kg H ₂]	[5,6]	0.52		
	H2 output, hourly	[ton /hr]		1.9		
	Annual utilization	[%]	[1]	85%		
	H2 output, annual	[kton/year]		14.1		
	Losses	[%]	[8]	0.5%		
	Net H2 output , annual	[kton/year]		14.08		
	Total direct cost, specific	[€/kW]	[1,2,4]	2.68E+03		
	System cost decline (annual)	[%]		-		
	Total direct cost	[€million]		2.53		
	Lifetime	[years]	[1,5,6]	15		
	Scaling factor	N/A	[8]	0.8335		
	Fixed OPEX rate	[%]	[8]	4%		
	Fixed OPEX	[€/year]		101,026		
	System footprint	[m ²]	[7]	110		

C2: H2 Liquefaction

C2: H2 Liquefaction							
Parameter name	Description	Unit	Source ID	Values/estimates			
				2020	2025	2030	2040
	Scale of the liquefaction plant	[TPD]	[1-4]	50	150	150	300
	System energy efficiency	[%]	4	0.73	0.77	0.81	0.87
	Specific energy consumption (SEC)	[kWh/kg H ₂]	[1-3]	12.5	10.0	8.0	5.0
	H ₂ output, hourly	[t/h]		2.1	6.3	6.3	12.5
	Annual utilization	[%]	3	95	95	95	95
	H ₂ output, annual	[kt/y]		17.3	52.0	52.0	104.0
	Total direct cost, specific	[€/kg LH ₂]		6.056	1.346	1.346	0.961
	System cost decline (annual)	[%]					
	Total direct cost	[M€]		105.0	70.0	70.0	100.0
	Scaling factor	N/A		0.7			
	Fixed OPEX	[M€/y]		0.21	0.14	0.14	0.20
	System footprint	[m ²]					

C3: Ammonia synthesis

C3: Ammonia synthesis														
Parameter name	Description	Unit	Source ID	Values/estimates										
				2020	2020	2020	2030	2030	2030	2040	2040	2040		
				Low	Mid	High	Low	Mid	High	Low	Mid	High		
	Scale of the NH3 synthesis plant	[ktpa]	(3, 15)	100		500								
20-30 bar syngas	Specific power consumption	[MWh/t NH3]	(1-3)	0.75										
	Specific H2 consumption	[t H2/t NH3]		0.177										
	Operating hours	[h/y]		8000										
	NH3 output, daily	[t/d NH3]		300.0		1500.0								
installed cost	Total direct cost, specific	[M€/tpd NH3 (capacity)]	(1-4)	0.267										
	installation factor			?										
with small scale plants, perhaps learning curves possible? >20ktpa = ok	System cost decline (annual)	[%]		?										
mature tech.	Scaling factor	N/A		0.65										
	Total direct cost	[M€]	(1-8)	80.0										
	Fixed OPEX	[M€/y]		2.0										
	System footprint	[m2]												

C4: Methanol synthesis

C4: Methanol synthesis												
Parameter name	Description	Unit	Source ID	Values/estimates								
				2020	2020	2020	2030	2030	2030	2040	2040	2040
				Low	Mid	High	Low	Mid	High	Low	Mid	High
	Scale of the Methanol plant	[MW]		317	317	317	317	317	317	317	317	317
	System energy efficiency	[%]		83	79	76	83	81	76	83	82	76
	Specific power consumption	[kWh/MJ MeOH]	3,4,6,7	0.008	0.014	0.017	0.008	0.011	0.017	0.008	0.010	0.017
	Specific H2 consumption	[MJ H2/MJ MeOH]	1,3,4,8	1.17	1.22	1.25	1.17	1.20	1.25	1.17	1.19	1.25
	Specific CO2 consumption	[kg CO2/MJ MeOH]	6	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
	MeOH output, hourly	[t/h]		57	57	57	57	57	57	57	57	57
	Heat output	[MJ Heat/MJ MeOH]	6	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025
	Annual utilization	[%]		95	95	95	95	95	95	95	95	95
	MeOH output, annual	[kt/y]		475	475	475	475	475	475	475	475	475
	CO2 emissions, annual	[kt/y]		57	57	57	48	48	48	38	38	38
	Total direct cost, specific	[€/kW]	1,3,4,5	95	347	726	221	252	347	158	237	347
	System cost decline (annual)	%					-9	3	7	3	1	0
	Total direct cost	[M€]		30	110	230	70	80	110	50	75	110
	Scaling factor	N/A										
	Fixed OPEX	[M€/y]	1,2,3,4,7	1	4	9	2	2	3	1	2	3
		[m2]										

C5: LOHC hydrogenation

C5: LOHC hydrogenation							
Parameter name	Description	Unit	Source ID	Values/estimates			
				2020	2025	2030	2040
	Scale of the hydrogenation plant	[MW]	2	1037			
	System energy efficiency	[%]	5	69.17			
	MCH output	TPD	3	11507			
	Specific power consumption	[kWh/kg H2]	3	0.4			
	Heat released	[kWh/kg H2]	[3,4]	8.8			
	H2 output, hourly	[t/h]	2	31			
	Annual utilization	[%]	1	95.0			
	H2 output, annual	[kt/y]	2	259			
	Total direct cost, specific	[€/kW]		186			
	System cost decline (annual)	[%]					
	Total direct cost	[M€]	3	193			
	Scaling factor	N/A	3	0.7			
	Fixed OPEX	[M€/y]	3	0.4			
	System footprint	[m2]					

C6a: Formic acid synthesis

C6a: Formic acid synthesis												
Parameter name	Description	Unit	Source ID	Values/estimates								
				2020	2020	2020	2030	2030	2030	2040	2040	2040
				Low	Mid	High	Low	Mid	High	Low	Mid	High
Scale of the formic acid synthesis plant		[ktpa]	1			12			100			
Specific power consumption		[MWh/t Formic acid]	2			0.30						
Specific heat consumption (steam)		[MWh/t formic acid]	2			2.78						
CO2 consumption		[t/t formic acid]	2			0.83						
Specific H2 consumption		[t H2/t formic acid]	2			0.06						
Operating hours		[h/y]				8000						
Formic acid output, daily		[t/d formic acid]				36.0						
Total direct cost, specific		[M€/tpd formic acid] (capacity)				0.254						
System cost decline (annual)		[%]										
Scaling factor		N/A				0.6						
Total direct cost		[M€]	2			9.15						
Fixed OPEX		[M€/y]				0.27						
Variable OPEX		[M€/year]	2			8.40						
System footprint		[m2]										

C6b: Formic acid synthesis

C6b: Formic acid synthesis												
Parameter name	Description	Unit	Source ID	Values/estimates								
				2020	2020	2020	2030	2030	2030	2040	2040	2040
				Low	Mid	High	Low	Mid	High	Low	Mid	High
Scale of the formic acid synthesis		[ktpa]	1			12						
Specific power consumption		[MWh/t Formic acid]	2			2.40						
Specific heat consumption (steam)		[MWh/t formic acid]	2			9.69						
CO2 consumption		[t/t formic acid]	2			0.88						
Specific H2 production		[t H2/t formic acid]	2			0.041						
Specific O2 production		[t H2/t formic acid]				0.32						
Operating hours		[h/y]				8000						
Formic acid output, daily		[t/d formic acid]				36.0						
Total direct cost, specific		[M€/tpd formic acid]				1.167						
System cost decline (annual)		[%]										
Scaling factor		N/A				0.9						
Total direct cost		[M€]	2			42						
Fixed OPEX		[M€/y]				1.26						
Variable OPEX		[M€/year]										
System footprint		[m2]										

C7: NaBH₄ synthesis

C7: NaBH ₄ synthesis												
Parameter name	Description	Unit	Source ID	Values/estimates								
				2020	2020	2020	2030	2030	2030	2040	2040	2040
				Low	Mid	High	Low	Mid	High	Low	Mid	High
	Scale of the NaBH ₄ synthesis plant	[ktpa]	1	23.3	46.6	69.9						
	Specific power consumption	[kWh/kg NaBH ₄]	1		0.02							
	Specific heat consumption (steam)	[kWh/kg NaBH ₄]	1		10.36							
	Specific H ₂ production	[t H ₂ /t NaBH ₄]	1		0.053							
	GHG emissions	kg CO ₂ -eq/kg NaBH ₄	1		2.459							
	Operating hours	[h/y]	1		8000							
	NaBH ₄ output, daily	[t/d NaBH ₄]	1		139.8							
	Volumetric energy density	[GJ/m ³]	1		32							
	CAPEX	[M€]	1		106.0							
	Annualized CAPEX	[M€/y]	1		8.5							
	Annualized CAPEX	[€/kg H ₂ -eq]	1		3.4							
	OPEX	[M€/y]	1		376.0							
	OPEX	[€/kg H ₂ -eq]	1		151.0							
	TRL		1		9.0							
	System footprint	[m ²]			N/A							

SH1: Liquid shipping (LH2) deep-sea liquid bulk carrier

SH1: Liquid shipping (LH2) deep-sea liquid bulk carrier								
Parameter name	Description	Unit	Source ID	Values/estimates			2040	
				2020	2030	2040		
				min	avg	max		
	Storage tank size	[m ³]	4,6,7,8,9,10,11,12	50,000	75,000	150,000	200,000	160,000
MaxCapacity_LH2_vessel	Storage tank capacity	[ton LH2]	4,1	3,550	5,325	10,650	14,200	11,360
Fuel_use_LH2_ves	Specific power consumption	[GJ/km]	1.4	0.81		3.6		3.6
	fuel consumption while sailing	ton MGO/day	[12]		27.00	27.0	27.0	
Boil_loss_LH2	Boil-off rate	[%/day]	2.4	0.2		0.2%		0.2%
	boil off rate	kg/s	[12]		0.0	0.00045	0.0%	
	Loading and discharge losses	% of total load	4	2.0				2.0
	Annual utilization							
	Total installed cost, specific	[€/ ton LH2]	3,4,5,6,7,8,9,10,11,12	25,070.42	35117	35,211	35211	20,774.6
ScalingFactor_LH2	Scaling factor	[N/A]		0.7	0.7	0.7	0.7	0.7
CAPEX_LH2_vesse	Total direct cost	[M€]	4,5,6,7,8,9,10,11,12	89	187	375	500	236.0
	Fixed OPEX	[M€/year]	4,5,6,7,8,9,10,11,12	2	9	19	25	9.0
	Life time	[Years]	4	30		30		30
	System cost decline (annual)	[%]						
	System footprint	[m ²]						

SH2: Ammonia (NH₃)

SH2: Ammonia (NH ₃)						
Parameter name	Description	Unit	Source ID	Values/estimates		
				2020	2030	2040
	Storage tank size	[m ³]	1	82,000	175,000	
	Storage tank capacity	[ton NH ₃]	1	52,152	111,300	
	Specific power consumption	[GJ/km]	1	1.44		
	Boil-off rate	[%/day]	2	0.08		
	Loading and discharge losses	% of total load	1	0.0		
	Annual utilization					
	Total installed cost, specific	[€/ ton NH ₃]	1	1,231		
	Total direct cost	[M€]	1	64,175,000		
	Fixed OPEX	[M€/year]	1	2,680,870		
	Life time	[Years]	1	30		
	System cost decline (annual)	[%]				
	System footprint	[m ²]				

SH3: Methanol (MeOH)

SH3: Methanol (MeOH)						
Parameter name	Description	Unit	Source ID	Values/estimates		
				2020	2030	2040
	Storage tank size	[m ³]	1	120,000	120,001	200,000
	Storage tank capacity	[ton MeOH]	1	95,040	95,041	158,400
	Specific power consumption	[GJ/km]	1	1.51	1.51	
	Boil-off rate	[%/day]	1	0.00	0.00	
	Loading and discharge losses	% of total load	1	0.0	0.0	
	Annual utilization					
	Total installed cost, specific	[€/ ton MeOH]	1	515	515	
	Total direct cost	[M€]	1	48,960,000	48,960,000	
	Fixed OPEX	[M€/year]	1	2,513,335	2,513,335	
	Life time	[Years]	1	30	31	
	System cost decline (annual)	[%]				
	System footprint	[m ²]				

SH4: Liquid Organic Hydrogen Carrier (LOHC)

SH4: Liquid Organic Hydrogen Carrier (LOHC)						
Parameter name	Description	Unit	Source ID	Values/estimates		
				2020	2030	2040
	Storage tank size	[m ³]	1	120,000	120,000	200,000
	Storage tank capacity	[ton LOHC]	1	104,040	104,040	173,400
	Specific power consumption	[GJ/km]	1	1.51	1.51	
	Boil-off rate	[%/day]	1	0.00	0.00	0.00
	Loading and discharge losses	% of total load	1	0.0	0.0	
	Annual utilization					
	Total installed cost, specific	[€/ ton LOHC]	1	471	471	
	Total direct cost	[M€]	1	48,960,000	48,960,000	
	Fixed OPEX	[M€/year]	1	2,741,679	2,741,679	
	Life time	[Years]	1	30	31	
	System cost decline (annual)	[%]				
	System footprint	[m ²]				

SH5: (FA) also an LOHC

SH5: (FA) also an LOHC						
Parameter name	Description	Unit	Source ID	Values/estimates		
				2020	2030	2040
	Storage tank size	[m ³]	2	61,475		
	Storage tank capacity	[ton FA]	2	75,000		
	Specific power consumption	[GJ/km]	1	1.51		
	Boil-off rate	[%/day]	3	0.0	0.0	0.0
	Loading and discharge losses	% of total load	1	0.0		
	Annual utilization					
	Total installed cost, specific	[€/ ton FA]	2,1	467		
	Total direct cost	[M€]	2	35		
	Fixed OPEX	[M€/year]	2	1.825		
	Life time	[Years]	2	15		
	System cost decline (annual)	[%]				
	System footprint	[m ²]				

SH6: Potassium Borohydride (KBH₄, empty)

SH6: Potassium Boro Hydride (KBH ₄)						
Parameter name	Description	Unit	Source ID	Values/estimates		
				2020	2030	2040
	Storage tank size	[m ³]				
	Storage tank capacity	[ton LH ₂]				
	Specific power consumption	[GJ/km]				
	Boil-off rate	[%/day]				
	Loading and discharge losses	% of total load				
	Annual utilization					
	Total installed cost, specific	[€/ ton LH ₂]				
	Total direct cost	[M€]				
	Fixed OPEX	[M€/year]				
	Life time	[Years]				
	System cost decline (annual)	[%]				
	System footprint	[m ²]				

I1: High pressure pipeline GH2

I1: High pressure pipeline GH2												
Parameter name	Description	Unit	Source ID	Values/estimates								
				2020			2030			2040		
				Low	Mid	High	Low	Mid	High	Low	Mid	High
	transmission volume	[PJ]	5				70.70					
	Refurbishment of existing pipelines cost	[M€/km]	5, 7				0.84			0.28	0.40	0.50
	New pipeline cost	[M€/km]	5, 7				3.20			1.51	2.20	2.75
	Transport capacity	[GWth]	4				10 - 15					
	Levelized Cost of European Hydrogen Backbone	[€/kg/1000km]	7							0.11	0.16	0.21
	Pipeline size	[inch]	7				20.00	36.00	48.00	20.00	36.00	48.00
	Pipeline pressure	[bar]	7					50.00	80.00		50.00	80.00
	Max theoretical throughput	[GW]	7				1.20	4.70	16.90	1.20	4.70	16.90
	Loading and discharge losses	% of total load	1	0.00			0.00			0.00		
	Annual utilization	%	3, 4, 7	75			75		100	75.00		100.00
	Total direct cost	[M€/km]	2	0.25			0.50			0.64		
	Fixed OPEX	[M€/year]	1	0.13%			0.25%			0.00		
	Life time	[Years]	3	40			40			40.00		
	System cost decline (annual)	[%]	6				25					
	System footprint	[m2]										

I2: Compressor station GH2

I2: Compressor station GH2												
Parameter name	Description	Unit	Source ID	Values/estimates								
				2020			2030			2040		
				Low	Mid	High	Low	Mid	High	Low	Mid	High
	Storage tank size	[m ³]										
	Specific power consumption	[MWe/km]	2								0.190 - 0.330	
	Loading and discharge losses	% of total load	1	0.00			0.00				0.00	
	Annual utilization	[%]		95			95				99	
	Total installed cost, specific	[€/ ton H ₂]										
	Scaling factor	[N/A]										
	Compressor station Capex	[M€/MWe]	3.4	0.40	3.93	2.2-3.4-6.7	2.2-3.4-6.7				2.2-3.4-6.7	
	Compressor station fixed OPEX	[M€/year]	1	0.14			0.14				0.14	
	Compression (Hydrogen) cost	[M€/MWe]	1	1.55								
	Compression (Hydrogen) fixed OPEX	[M€/year]	1	0.06200								
	OPEX fixed + var	[M€/year]	4	9								
	Life time	[Years]	3	15-33			15-33				15-33	
	System cost decline (annual)	[%]										
	System footprint	[m ²]			1050							

I3: Cleaning station GH2 (empty)

I3: Cleaning station GH2						
Parameter name	Description	Unit	Source ID	Values/estimates		
				2020	2030	2040
	Cleaning and preparing pipeline	[M€/km]	1	0.3		
	Storage tank capacity	[ton LH2]				
	Specific power consumption	[GJ/km]				
	Boil-off rate	[%/day]				
	Loading and discharge losses	% of total load				
	Annual utilization					
	Total installed cost, specific	[€/ ton LH2]				
	Scaling factor	[N/A]				
	Total direct cost	[M€]				
	Fixed OPEX	[M€/year]				
	Life time	[Years]				
	System cost decline (annual)	[%]				
	System footprint	[m2]				

I4: Decentral GH2 pipeline (Last Mile)

I4: Decentral GH2 pipeline (Last Mile)						
Parameter name	Description	Unit	Source ID	Values/estimates		
				2020	2030	2040
	transmission volume	[PJ]				
	Molecular weight of hydrogen	[g/mol]		2.016		
	Hydrogen gas pipeline dynamic viscosity	[Pa.s]		0.0000086		
	Surface roughness of pipeline	[m]		0.00005		
	Minimal inlet pressure	[bar]	1	30.00		
	Maximal inlet pressure	[bar]	2,5,6,7	70.00		
	Minimum pressure within pipelines	[bar]	8	10.00		
	Outlet pressure	[bar]	1	30.00		
	Maximum hydrogen velocity	[m/s]	2,3,4	20.00		
	Scaling margin	[%]	4	10.00		
	Diameter existing high pressure transmission pipe	[m]	8	0.91		
	Diameter existing RTL (40 bar) pipeline	[m]	9	0.2065		
	Investment cost factor A pipeline cost function	N/A	7, 10	1021.70		
	Investment cost factor B pipeline cost function	N/A	7, 11	-20393.00		
	Investment cost factor C pipeline cost function	N/A	7, 12	642720.00		
	Pipeline investment cost reduction if existing pipelines	[%]	11	70.00		
	Fixed OPEX new pipelines	[%/y]		1.00		
	Fixed OPEX reused pipelines	[%/y]		3.33		
	Refurbishment of existing pipelines cost	[M€/km]				
	New pipeline cost	[M€/km]				
	Transport capacity	[GWth]				
	Transport cost	[€/kg]				
	Loading and discharge losses	% of total load		0.00		
	Annual utilization	%				
	Total direct cost	[M€/km]				
	Fixed OPEX	[M€/year]				
	Life time	[Years]		40		
	System cost decline (annual)	[%]				
	System footprint	[m2]				

I5: LH2 Truck

I5 LH2 Truck												
Parameter name	Description	Unit	Source ID	Values/estimates								
				2020			2030			2040		
				Low	Mid	High	Low	Mid	High	Low	Mid	High
	Diesel truck CAPEX	[€]	1,14	100,000	125,000	150,000	109,000	136,250	163,500	118,810	148,513	178,215
	Diesel truck fixed OPEX	[€/year]	10	7,300	12,600	16,000	7,300	12,600	16,000	7,300	12,600	16,000
	Diesel truck lifetime	[Years]	1,16	5	8	13	5	8	13	5	8	13
	Diesel truck fuel use	[Litres/km]	11	0.21	0.33	0.44	0.16	0.24	0.32	0.12	0.19	0.25
	FCEV truck CAPEX	[€]	12	300,000	400,000	550,000	135,000	180,000	247,500	135,000	180,000	247,500
	FCEV truck OPEX	[€/year]	12	13,094	22,600.00	28,698	5,416	9,348	11,871	5,416	9,348	11,871
	FCEV truck lifetime	[Years]		8	10	12	8	10.00	12	8	10	12
	FCEV truck fuel use	[kg H2/km]	13	0.06	0.09	0.12	0.06	0.09	0.12	0.06	0.09	0.12
	Truck utilization	[%]	1,4,5	23	75.0	80	23	75	80	23	75	80
	Average driving speed	[km/hour]	1	30	50	70	30	50	70	30	50	70
	Driver wage	[€/hour]	10	20	25.0	40	20	35	40	20	25	40
	Trailer CAPEX	[€]	1		860,000			860,000			860,000	-
	Trailer fixed OPEX	[€/year]	1		17,200.0			17,200.00			17,200	-
	Lifetime trailer	[Years]	1		12			12			12	
	Trailer net carrying capacity	[kg]	1		4,300			4,300			4,300	
	Trailer loading time	[hours]	1		3			3			3	
	Storage tank size	[m³]			61			61			61	
	Storage tank capacity	[ton LH2]										
	Specific power consumption	[GJ/km]										
	Boil-off rate	[%/day]	17	1.00	3.00	5.00	1.00	3.00	5.00	0.01	0.03	0.04
	Loading and discharge losses	% of total load										
	Annual utilization											
	Total installed cost, specific	[€/ ton LH2]										
	Total direct cost	[M€]										
	Fixed OPEX	[M€/year]										
	Life time	[Years]										
	System cost decline (annual)	[%]										
	System footprint	[m2]										

I6: GH2 Truck

I6 GH2 Truck												
Parameter name	Description	Unit	Source ID	Values/estimates								
				2020	2020	2020	2030	2030	2040	2040	2040	2040
				Low	Mid	High	Low	Mid	High	Low	Mid	High
	Diesel truck CAPEX	[€]	1,14	100,000	125,000	150,000	109,000	136,250	163,500	118,810	148,513	178,215
	Diesel truck fixed OPEX	[€/year]	10	7,300	12,600	16,000	7,300	12,600	16,000	7,300	12,600	16,000
	Diesel truck lifetime	[Years]	1,16	5	8	13	5	8	13	5	8	13
	Diesel truck fuel use	[Litres/km]	11	0.21	0.33	0.44	0.16	0.24	0.32	0.12	0.19	0.25
	FCEV truck CAPEX	[€]	12	300,000	400,000	550,000	135,000	180,000	247,500	135,000	180,000	247,500
	FCEV truck OPEX	[€/year]	12	13,094	22,600.00	28,698	5,416	9,348	11,871	5,416	9,348	11,871
	FCEV truck lifetime	[Years]		7	10	13	7	10.00	13	7	10	13
	FCEV truck fuel use	[MJ/km]	13	0.06	0.09	0.12	0.06	0.09	0.12	0.06	0.09	0.12
	Truck utilization	[%]	1,4,5	23	75.0	80	23	75	80	23	75	80
	Average driving speed	[km/hour]	1	30	50	70	30	50	70	30	50	70
	Driver wage	[€/hour]	10	20	25.0	40		35				
	Trailer CAPEX	[€]	1,17	460,000	570,000.0	1,000,000	460,000	570,000.00	1,000,000	460,000	570,000	1,000,000
	Trailer fixed OPEX	[€/year]	1	9,200	11,400	20,000	9,200.00	11,400.00	20,000.00	20,000	9,200	11,400
	Lifetime trailer	[Years]	1		12.0			12			12	
	Trailer net carrying capacity	[kg]	1,17	650	900.0	1,500	650	900	1,500	650	900	1,500
	Trailer loading time	[hours]	1,17	1.0	1.5	2.0	1.0	1.5	2.0	1.0	1.5	1.5
	Storage tank size	[m ³]										
	Storage tank capacity	[ton gH2]										
	Specific power consumption	[GJ/km]										
	Boil-off rate	[%/day]										
	Loading and discharge losses	% of total load										
	Annual utilization											
	Total installed cost, specific	[€/ ton gH2]										
	total direct cost	[M€]										
	Fixed OPEX	[M€/year]										
	Life time	[Years]										
	System cost decline (annual)	[%]										
	System footprint	[m ²]										

I7: GH2 Small Ship (empty)

I7 GH2 Small Ship						
Parameter name	Description	Unit	Source ID	Values/estimates		
				2020	2030	2040
	Storage tank size	[m ³]				
	Storage tank capacity	[ton NH ₃]				
	Specific power consumption	[GJ/km]				
	Boil-off rate	[%/day]				
	Loading and discharge losses	% of total load				
	Annual utilization					
	Total installed cost, specific	[€/ ton NH ₃]				
	Total direct cost	[M€]				
	Fixed OPEX	[M€/year]				
	Life time	[Years]				
	System cost decline (annual)	[%]				
	System footprint	[m ²]				

I9: NH3 Truck

I9 NH3 Truck												
Parameter name	Description	Unit	Source ID	Values/estimates								
				2020			2030			2040		
				Low	Mid	High	Low	Mid	High	Low	Mid	High
	Diesel truck CAPEX	[€]	1.2	100,000	125,000	150,000	109,000	136,250	163,500	118,810	148,513	178,215
	Diesel truck fixed OPEX	[€/year]	1.2	7,300	12,600	16,000	7,300	12,600	16,000	7,300	12,600	16,000
	Diesel truck lifetime	[Years]	1.2	5	8	13	5	8	13	5	8	13
	Diesel truck fuel use	[Litres/km]	1	0.21	0.33	0.44	0.16	0.24	0.32	0.12	0.19	0.25
	FCEV truck CAPEX	[€]		300,000	400,000	550,000	135,000	180,000	247,500	135,000	180,000	247,500
	FCEV truck OPEX	[€/year]		13,094	22,600	28,698	5,416	9,348	11,871	5,416	9,348	11,871
	FCEV truck lifetime	[Years]		8	10	12	8	10	12	8	10	12
	FCEV truck fuel use	[MJ/km]	2	0.06	0.09	0.12	0.06	0.09	0.12	0.06	0.09	0.12
	Truck utilization	[%]	1,4,5	23	75	80	23	75	80	23	75	80
	Average driving speed	[km/hour]	1	30	50	70	30	50	70	30	50	70
	Driver wage	[€/hour]	1	20	25	40	20	35	40	20	25	40
	Trailer CAPEX	[€]	2		189,200.00			189,200.00			189,200	
	Trailer fixed OPEX	[€/year]	2		3,784.00			3,784.00			3,784	
	Lifetime trailer	[Years]	2		20			20.00			20	
	Trailer net carrying capacity	[kg H2]	2, 10,11	1,800	2,600	3,600	1,800.00	2,600.00	3,600.00	1,800	2,600	3,600
	Trailer loading time	[hours]	2		1.5			1.5			1.5	
	Storage tank size	[m ³]	11	25	35	50	25	35	50	25	35	50
	Storage tank capacity	[ton NH3]		12	17	24	12	17	24	12	17	24
	Specific power consumption	[GJ/km]										
	Boil-off rate	[%/day]										
	Loading and discharge losses	% of total load										
	Annual utilization											
	Total installed cost, specific	[€/ ton NH3]										
	Total direct cost	[M€]										
	Fixed OPEX	[M€/year]										
	Life time	[Years]										
	System cost decline (annual)	[%]										
	System footprint	[m2]										

I10: NH₃ Ship

I10		NH ₃ Ship				
Parameter name	Description	Unit	Source ID	Values/estimates		
				2020	2030	2040
	Storage tank size	[m ³]	[3]	2,280	2,280	2,280
	Storage tank capacity	[ton NH ₃]	[3]	1,100	1,100	1,100
	Specific power consumption	[GJ/km]	[4]	3.80	4	4
	Boil-off rate	[%/day]		0.00	-	-
	Loading and discharge losses	% of total load		0.0	-	-
	Annual utilization				-	-
	Total installed cost, specific	[€/ ton NH ₃]		10,700	10,700	10,700
	Total direct cost	[M€]		12	12	12
	Fixed OPEX	[M€/year]			-	-
	Life time	[Years]	[4]	30	30	30
	System cost decline (annual)	[%]			-	-
	System footprint	[m ²]	[3]	1231.00	1,231	1,231

I11: NH₃ Train

I11 NH ₃ Train						
Parameter name	Description	Unit	Source ID	Values/estimates		
				2020	2030	2040
	CAPEX rail tank car	[€]	1, 2	163,000	163,000	163,000
	Fixed OPEX rail tank car	[€/year]		3,260	3,260	3,260
	Lifetime rail tank car	[years]	2	25	25	25
	Utilization rail tank car	[%]	3	0.96	1	1
	Carrying capacity rail tank car	[kg]	4	54,100	54,100	54,100
	Weight (unloaded) rail tank car	[kg]	4	35,900	35,900	35,900
	Freight costs liquid rail transport	[€/ton/km]	5	0.015	0	0
	(Un)loading costs liquid rail freight at station	[€/ton]	5	7.055	7	7
	Energy use rail transport	[kWh/km/ton]	6	0.02	0	0
	Average speed rail transport	[km/hour]		70	70	70
	Departure options of liquid freight trains	[#/day]	3	1	1	1
	Storage tank size	[m ³]		127	127	127
	Storage tank capacity	[ton NH ₃]		67	67	67
	Specific power consumption	[GJ/km]			-	-
	Boil-off rate	[%/day]		0.00	-	-
	Loading and discharge losses	% of total load			-	-
	Annual utilization	[%]		75	75	75
	Total installed cost, specific	[€/ ton NH ₃]		2,433	2,433	2,433
	Total direct cost	[M€]			-	-
	Fixed OPEX	[M€/year]			-	-
	Life time	[Years]			-	-
	System cost decline (annual)	[%]			-	-
	System footprint	[m ²]			-	-

I12: MeOH Truck

I12 MeOH Truck												
Parameter name	Description	Unit	Source ID	Values/estimates								
				2020	2020	2020	2030	2030	2040	2040	2040	2040
				Low	Mid	High	Low	Mid	High	Low	Mid	High
	Storage tank size	[m ³]	1		41			41			41	
MaxCapacity_MeOH_bunker	Storage tank capacity	[ton MeOH]	2		33			33			33	
!_use_MeOH_bun	Specific power consumption	[GJ/km]	3		0.01			0.01			0.0	
	Boil-off rate	[%/day]			0.00			0.00			0.00	
	Loading and discharge losses	% of total load			0.0			0.0			0.0%	
	Annual utilization				1			1			1.0	
	Total installed cost, specific	[€/ ton MeOH]			4,619			4,619			€ 4,619	
SF_MeOH_bunker	Scaling factor	[N/A]			1			1			1.0	
APEX_MeOH_bunk	Total direct cost	[€]	3		#####			#####			#####	
FOPEX_MeOH_bun	Fixed OPEX	[M€/year]	4		€ 0.08			€ 0.08			€ 0.08	
	Life time	[Years]			5.00			5.00			5.00	
stance_MeOh_bun	Average driving distance	[km]			100.00			100.00			100.00	
!_cost_MeOH_bun	Cost of fuel per GJ	€/GJ	5		43.39			43.39			43.39	
eliveries_MeOH_t	Max bunker deliveries per day	#			3.00			3.00			3.00	
stime_MeOH_Bunk	% of days the asset can actually be used	%			0.96			0.96			0.96	

I13: Methanol (MeOH) bunker barge

I13 Methanol (MeOH) bunker barge													
Parameter name	Description	Unit	Source ID	Values/estimates									
				2020	2020	2020	2030	2030	2030	2040	2040	2040	
				Low	Mid	High	Low	Mid	High	Low	Mid	High	
	Storage tank size	[m ³]	1		3,000			3,000				3,000	
MaxCapacity_MeOH_bunker	Storage tank capacity	[ton MeOH]	1		2,257			2,257				2,257	
Fuel_use_MeOH_bunker	Specific power consumption	[GJ/km]	7		0.45			0.45				0.45	
Boil_Loss_MeOH_bunker	Boil-off rate	[%/day]	6		0.00%			0.00%				0.00%	
	Loading and discharge losses	% of total load			0%			0%				0%	
	Total installed cost, specific	[€/ ton MeOH]			€ 4,430			€ 4,430				€ 4,430	
<i>SF_MeOH_bunker</i>	<i>Scaling factor</i>	<i>[N/A]</i>			0.7			0.7				0.7	
Uptime_MeOH_Bunker	% of days the asset can actually be used	%			96%			96%				96%	
CAPEX_MeOH_bunker	Total direct cost	[€]	3, 4		#####			#####				#####	
FOPEX_MeOH_bunker	Fixed OPEX	[M€/year]	5		1.75			1.75				1.75	
Lifetime_MeOH_Bunker	Life time	[Years]	2		25			25				25	
Distance_MeOH_bunker	Average sailing distance	[km]			60			60				60	
Fuel_cost_MeOH_bunker	Fuel cost	€/GJ											
Max_deliveries_MeOH_bunker	max bunker deliveries per day	#			3			3				3	

I14: MeOH Train (empty)

I14		MeOH Train		Values/estimates								
Parameter name	Description	Unit	Source ID	2020	2020	2020	2030	2030	2030	2040	2040	2040
				Low	Mid	High	Low	Mid	High	Low	Mid	High
	Storage tank size	[m ³]										
	Storage tank capacity	[ton NH3]										
	Specific power consumption	[GJ/km]										
	Boil-off rate	[%/day]										
	Loading and discharge losses	% of total load										
	Annual utilization											
	Total installed cost, specific	[€/ ton NH3]										
	Total direct cost	[M€]										
	Fixed OPEX	[M€/year]										
	Life time	[Years]										
	System cost decline (annual)	[%]										
	System footprint	[m2]										

I15: LOHC Truck

I15 LOHC Truck				Values/estimates								
Parameter name	Description	Unit	Source ID	2020	2020	2020	2030	2030	2040	2040	2040	2040
				Low	Mid	High	Low	Mid	High	Low	Mid	High
	Diesel truck CAPEX	[€]	1,14	100,000	125,000	150,000	109,000	136,250	163,500	118,810	148,513	178,215
	Diesel truck fixed OPEX	[€/year]	10	7,300	12,600	16,000	7,300	12,600	16,000	7,300	12,600	16,000
	Diesel truck lifetime	[Years]	1,16	5	8	13	5	8	13	5	8	13
	Diesel truck fuel use	[Litres/km]	11	0	0	0	0	0	0	0	0	0
	FCEV truck CAPEX	[€]	12	300,000	400,000	550,000	135,000	180,000	247,500	135,000	180,000	247,500
	FCEV truck OPEX	[€/year]	12	13,094	22,600	28,698	5,416	9,348	11,871	5,416	9,348	11,871
	FCEV truck lifetime	[Years]	0	8	10	12	8	10	12	8	10	12
	FCEV truck fuel use	[MJ/km]	13	0	0	0	0	0	0	0	0	0
	Truck utilization	[%]	1,4,5	23	75	80	23	75	80	23	75	80
	Average driving speed	[km/hour]	1	30	50	70	30	50	70	30	50	70
	Driver wage	[€/hour]	10	20	25	40	20	35	40	20	25	40
	Trailer CAPEX	[€]	1		150,000.0			150,000.00			150,000	
	Trailer fixed OPEX	[€/year]	1		3,000.0			3,000.00			3,000	
	Lifetime trailer	[Years]	1		12.0			12			12	
	Trailer net carrying capacity	[kg]	1		1,800.0			1,800			1,800	
	Trailer loading time	[hours]	1		1.5			1.5			2	
	Storage tank size	[m ³]	16		50.0							
	Storage tank capacity	[ton LOHC]	0		42							
	Specific power consumption	[GJ/km]	0		0.00							
	Boil-off rate	[%/day]	17		0.00							
	Loading and discharge losses	% of total load	0		0.0							
	Annual utilization		0									
	Total installed cost, specific	[€/ ton LOHC]	0		3,571							
	Total direct cost	[M€]	0									
	Fixed OPEX	[M€/year]	0									
	Life time	[Years]	[20]									
	System cost decline (annual)	[%]	0									
	System footprint	[m ²]	0									

I16: LOHC Ship (empty)

I16 LOHC Ship												
Parameter name	Description	Unit	Source ID	Values/estimates								
				2020			2030			2040		
				Low	Mid	High	Low	Mid	High	Low	Mid	High
	Storage tank size	[m ³]										
	Storage tank capacity	[ton NH ₃]										
	Specific power consumption	[GJ/km]										
	Boil-off rate	[%/day]										
	Loading and discharge losses	% of total load										
	Annual utilization											
	Total installed cost, specific	[€/ ton NH ₃]										
	Total direct cost	[M€]										
	Fixed OPEX	[M€/year]										
	Life time	[Years]										
	System cost decline (annual)	[%]										
	System footprint	[m ²]										

I17: LOHC Train (empty)

I17 LOHC Train												
Parameter name	Description	Unit	Source ID	Values/estimates								
				2020			2030			2040		
				Low	Mid	High	Low	Mid	High	Low	Mid	High
	Storage tank size	[m ³]										
	Storage tank capacity	[ton NH ₃]										
	Specific power consumption	[GJ/km]										
	Boil-off rate	[%/day]										
	Loading and discharge losses	% of total load										
	Annual utilization											
	Total installed cost, specific	[€/ ton NH ₃]										
	total direct cost	[M€]										
	Fixed OPEX	[M€/year]										
	Life time	[Years]										
	System cost decline (annual)	[%]										
	System footprint	[m ²]										

ST1: CH₂ Storage -HP Vessels

ST1: CH ₂ Storage -HP Vessels							
Parameter name	Description	Unit	Source ID	Values/estimates			
				2020	2025	2030	2040
	Storage capacity (mass)	[kg]	[1,2,5]	500			
	storage pressure	[bar]		200			
	storage capacity (volume)	[m ³]	[7]	32			
	storage capacity (energy)	[MWh]		16.6			
	System energy efficiency	[%]					
	Scaling factor (economic)	N/A	[7]	0.95			
	Total direct cost, specific	[€/kg]	[5,8]	535			
	System cost decline (annual)	[%]	[1,4]	10%			
	Total direct cost	[M€]		0.27			
	Fixed OPEX	[%]	[1,3]	4%			
	Fixed OPEX	[€/y]	[1,3]	10,700			
	Life time	[Years]	[3]	25			
	System footprint	[m ²]					

ST2: CH₂ Storage -Salt Caverns

ST2: CH ₂ Storage -Salt Caverns							
Parameter name	Description	Unit	Source ID	Values/estimates			
				2020	2025	2030	2040
	Scale /size	[m ³]	[1,2,3,8]	1,000,000	1,000,000	1,000,000	1,000,000
	Diameter	[m]	[1,8]	65			
	Height	[m]	[1,8]	300			
	Depth of LCCS	[m]	[1, 8]	1,000			
	Maximum pressure	[bar]	[1,2]	181			
	minimum pressure	[bar]	[1,2]	77			
	Temperature (average)	[°C]	[9]	40			
	Storage capacity /working gas volume	[Nm ³]	[11]	78,266,880			
	Storage capacity/ working gas mass	[ton]	[11]	7,036			
	Storage capacity /energy stored	[GWh]	[11]	235			
	Cushion gas (volume)	[Nm ³]		64,430,489			
	Cushion gas (mass)	[ton]		5792			
	Total gas volume in the cavern	[Nm ³]		142,697,369			
	Injection rate	[Nm ³ /day]	[2]	5,200,000			
	Injection rate	[GW]	[2]	0.61			
	Annual Utilization	[%]		99			
	CAPEX for cavern, specific	[€/m ³]	[5]	40			
	CAPEX for cavern	[€ million]		40			
	Cost(price) of cushion gas	[€/kg]	[10]	2.63			
	CAPEX for cushion gas	[€ million]		15.23			
	Total CAPEX	[€ million]		55.23			
	Fixed OPEX rate	[%]	[2,8]	4%			
	Fixed OPEX	[€ million/ year]		2.21			
	CAPEX, specific	[€/kg]		7.85			
	CAPEX, specific	[€/kWh]		0.24			
	System cost decline (annual)	[%]	[3]	10			
	Life time	[Years]	[2]	30			
	System footprint	[m ²]					
	TRL			6			

ST3: Liquid storage (LH2)

ST3: Liquid storage (LH2)								
Parameter name	Description	Unit	Source ID	Values/estimates				
				2020	2030	2030	2030	2040
				2020	Low	Mid	High	2040
DesignCapacity_LH2_storageunit	Storage tank capacity	[m ³ /tank]	[1,2,6]	8,000		100,000		
	Storage tank capacity	[ton]	[6]	626		7080		
	Storage tank capacity	[MWh]		20,870				
	Specific power consumption	[kWh/kg]	[5,6]	0.6		0.1		
	diameter	m	[6]			62.0		
Storage_utilization	Annual utilization	[%]		95.0		95.0		
	losses	[%/year]	[2,6]	11.00		18.3		
Storage_capacity_	factor for buffer capacity	[N/A]	[5]	1.3				
	Total installed cost, specific	[€/kg LH2]	[2,6]	25		13.17		
	Total installed cost, specific	[€/kWh]	[3]	0.75				
	Scaling factor	[N/A]	[6]			0.7		
CAPEX_LH2_storag	Total direct cost /CAPEX	[M€]	[1-5,6]	15.65		93.24		
	Fixed OPEX	[M€/year]	[2,5]	0.3				
	Variable OPEX	[M€/year]						
	Life time	[Years]	[5]	30				
	System cost decline (annual)	[%]						
	System footprint	[m ²]						

ST4: Liquid NH3 tanks

ST4: Liquid NH3 tanks												
Parameter name	Description	Unit	Source ID	Values/estimates								
				2020	2020	2020	2030	2030	2030	2040	2040	2040
				Low	Mid	High	Low	Mid	High	Low	Mid	High
	Max. NH3 storage tank capacity	[m3]	(2)		80,000.0							
	Max. NH3 storage tank capacity	[t NH3]			54480							
	Specific power consumption	[kWh/t NH3]										
	Total installed cost, specific	[€/t NH3]			2000							
	Scaling anchor point	[t NH3]			5000							
	Total direct cost (@ max capacity)	[M€]			49.5							
	Scaling factor	N/A			0.67							
	Fixed OPEX	[M€/y]			1.0							
	System footprint	[m2]										

ST5: Liquid storage (MeOH)

ST5: Liquid storage (MeOH)							
Parameter name	Description	Unit	Source ID	Values/estimates			
				2020	2025	2030	2040
	Storage tank size	[m ³]	[1]	50,000			
	Storage tank capacity	[ton MEOH]	[1,3,4]	31,680			
	Storage tank capacity	[kg H ₂]		4,950,000			
	Specific power consumption	[kWh/ ton MEOH]	[1,2]	-			
	Annual utilization	[%]		99			
	Total installed cost, specific	[€/ ton MEOH]	[2]	472.5			
	Scaling factor	[N/A]					
	Total direct cost	[M€]	[1]	15			
	Fixed OPEX	[M€/year]	[1]	0.1			
	Life time	[Years]	[1]	30			
	System cost decline (annual)	[%]					
	System footprint	[m ²]		500.0			

ST6: Liquid storage (LOHC)

ST6: Liquid storage (LOHC)							
Parameter name	Description	Unit	Source ID	Values/estimates			
				2020	2025	2030	2040
	Storage tank capacity	[m ³ /tank]	[1]	50,000			
	Storage tank capacity	[ton MCH]	[2,3]	38,500			
	Storage tank capacity	[kg H ₂]		2,355,000			
	Storage tank capacity	[MWh]		78,280			
	storage pressure	[bar]		1			
	Annual utilization	[%]		98			
	Total installed cost, specific	[€/ ton MCH]		324.68			
	Scaling factor	[N/A]	[3]	0.65			
	Total direct cost	[M€]	[1]	12.5			
	Fixed OPEX	[€/year]	[1]	25000.0			
	Life time	[Years]	[1,2]	30			
	System cost decline (annual)	[%]					
	System footprint	[m ²]		1250			

R2: NH3 dissociation

R2: NH3 dissociation							
Parameter name	Description	Unit	Source ID	Values/estimates			
				2020	2020	2030	2040
				Low	Mid	Mid	Mid
	NH3 feed flow	[t/h NH3]			50		
	Max H2 fuel output	[MW th]			181		
	Heat of reaction	[MWh/t NH3]	(1-2)		0.88		
	Process thermal efficiency	[%]			70		
	Heat input required (at rated capacity)	[MW th]			51.67		
	Power input required (at rated capacity)	[MW el]			--		
	Total CAPEX (installed) (@ max capacity)	[M€]	(3)		101.4		
	Total direct cost (@ max capacity)	[M€]			63.0		
largest = 2mw outp	learning curves?						
largest = 2mw outp	Scaling factor	N/A			0.7		
	Fixed OPEX	[M€/y]			1.6		
	System footprint	[m2]					

R3: MeOH reforming

R3: MeOH reforming						
Parameter name	Description	Unit	Source ID	2020	2030	2040
				Mid	Mid	Mid
	MeOH feed flow	[kg/hr MeOH]	[2,3]	630		
	Water feed flow	[kg/h]	[2,3]	360		
	Operating pressure	[bar]	[8]	10		
	Operating Temperature	[°C]	[1, 8]	200		
	PSA operating pressure			20		
	H2 output	[Nm ³ /h]	[3]	1,000.00		
	H2 output	[kg/h]		88.70		
	Electricity consumption	[kW el]	[3]	45.00		
	Heat input required	[kW the]		-		
	Utilization	[%]		90%		
	Process thermal efficiency	[%]	[6]	84%		
	Total energy required	[kWh/kg H ₂]		0.51		
	Reference H2 output	[m ³ /h]	[8]	15.00		
	Scaling factor	[n/a]		0.70		
	Life time	[y]		20.00		
	Specific CAPEX of reference	[€/kg]		1.33		
	Total CAPEX (reference capacity)	[M€]	[8]	0.279		
	Total CAPEX (installed)	[M€]		10.57		
	Fixed OPEX rate	[%]	[8]	3%		
	Fixed OPEX	[M€/y]		0.317		
	System footprint	[m ²]				

R4: LOHC dehydrogenation

R4 LOHC dehydrogenation							
Parameter name	Description	Unit	Source ID	Values/estimates			
				2020	2025	2030	2040
	Scale of the dehydrogenation plant	[MW]					
	System energy efficiency	[%]					
	H2 output	TPD	1			300	
	Specific power consumption	[kWh/kg H2]	1			0.37	
	Heat DEMAND	[kWh/kg H2]	1			9.0	
	Hydrogen losses	[%]	1			1.0	
	H2 output, hourly	[t/h]					
	Annual utilization	[%]				95.0	
	H2 output, annual	[kt/y]					
	O2 output, annual	[kt/y]					
	Total direct cost, specific	[€/kW]					
	System cost decline (annual)	[%]					
	Total direct cost	[M€]	1			30.0	
	Scaling factor	N/A	1			0.6	
	Fixed OPEX	[M€/y]	1			0.9	
	System lifetime	[years]	1			20.0	
	System footprint	[m2]					

R6: KBH4 Decomposition (empty)

R6 KBH4 Decomposition							
Parameter name	Description	Unit	Source ID	Values/estimates			
				2020	2025	2030	2040

R9: NaBH4 reconversion

R9: NaBH4 reconversion												
Parameter name	Description	Unit	Source ID	Values/estimates								
				2020	2020	2020	2030	2030	2030	2040	2040	2040
				Low	Mid	High	Low	Mid	High	Low	Mid	High
	Capacity	[ktonne H2/y]	1	5	10	15						
	Water consumption	[m3/kg H2]	1		0.0006							
	electricity consumption	[kWh/kg H2]	1		0.0193							
	Heat input required	[MJ/kg H2]	1		37.3287							
	GHG emissions	[kg CO2-eq/kg H2]	1		2.45937							
	Roundtrip efficiency	[%]	1		47%							
	TRL		1		2							
	Total energy required	[kWh/kg H ₂]	1		15.3							
	CAPEX	[M€]	1		3.0							
	Annualized CAPEX	[M€/y]	1		0.2							
	OPEX	[M€/y]	1		50.0							
	System footprint	[m ²]			N/A							

T1: Liquid Hydrogen (LH2)

T1: Liquid Hydrogen (LH2)							
Parameter name	Description	Unit	Source ID	Values/estimates			
				2020	2025	2030	2040
Import Terminal							
Jetty	Capacity	[ton/year]	[1]	4,000,000	4000000.0	4000000.0	4000000.0
	Call size of vessel	[ton]					
	Vessel turnaround time	[hours]					
	Mooring time , tm	[hours]					
	Unloading time, tu	[hours]		0.00	0.0	0.0	0.0
	Investment cost, loading equipment	[€ million/jetty]	[1]	1.00	1.0	1.0	1.0
	Investment cost, jetty	[€ million/jetty]	[1]	2.96	3.0	3.0	3.0
	# of Jetty			1.00	1.0	1.0	1.0
	Total Investment cost	[€million]		3.96	4.0	4.0	4.0
	Fixed OPEX rate	[%]	[1]	2%	0.02	0.02	0.02
	Fixed OPEX	[€/year]	[1]	79200.00	79200	79200	79200
	scaling factor	[NA]	[2]	0.67	0.67	0.67	0.67
	Lifetime	[years]	[1]	30.00	30.0	30.0	30.0
Pipeline	Unloading flow rate	[ton/year]		4,000,000	4000000	4000000	4000000
	Unloading flow rate	[m ³ /hr]		7145.87	7145.8686	7145.8686	7145.8686
	Pipeline length	[km]	[6]	1	1	1	1
	pipeline diameter	[inch]		32	32	32	32
	Pumping energy consumption	[kWh/kg]		0	0.1	0.1	0.1
	Pipeline investment, specific	[€ million /km]	[6]	19.00	19	19	19
	Pipeline investment	[€ million]		19	13	13	13
	Fixed Opex rate	[%]	[6]	2.5%	0.025	0.025	0.025
	Fixed Opex	[€/year]		475,000	325000	325000	325000
	lifetime			26	26	26	26
Total							
	Total import terminal investment cost	[€million]		222.96	217.0	217.0	217.0
	Total import terminal OPEX	[€million/year]		4.55	4.4	4.4	4.4

T2: Ammonia (NH3)

T2: Ammonia (NH3)									
Parameter name	Description	Unit	Source ID	Values/estimates					
				2020	2020	2020	2025	2030	2040
Import Terminal				Low	Mid	High			
Jetty	Capacity	[ton/year]	[1]		4000000.00				
	Call size of vessel	[ton]							
	Vessel turnaround time	[hours]							
	Mooring time , tm	[hours]							
	Unloading time, tu	[hours]			0.00				
	Investment cost, loading equipment	[€ million/jetty]	[1]		1.00				
	Investment cost, jetty	[€ million/jetty]	[1]		2.96				
	# of Jetty				1.00				
	Total Investment cost	[€ million]			3.96				
	Fixed OPEX rate	[%]	[1]		2%				
	Fixed OPEX	[€/year]	[1]		79200.00				
	scaling factor	[NA]	[2]		0.67				
	Lifetime	[years]	[1]		30.00				
	Pipeline	Unloading flow rate	[ton/year]			4000000.00			
Unloading flow rate		[m ³ /hr]			7167.07				
Pipeline length		[km]			1				
pipeline diameter		[inch]			32				
Pumping energy consumption		[kWh/kg]			0				
Pipeline investment, specific		[€ million /km]	[1]		13.00				
Pipeline investment		[€ million]			13				
Fixed Opex rate		[%]			2.5%				
Fixed Opex		[€/year]			325,000				
lifetime					26				
Total									
	Total import terminal investment cost	[€ million]			76.96				
	Total import terminal OPEX	[€ million/year]			1.60				

T3: Methanol (MeOH, empty)

T3: Methanol (MeOH)							
Parameter name	Description	Unit	Source ID	Values/estimates			
				2020	2025	2030	2040
Import Terminal							
Jetty	Capacity	[ton/year]	[1]				
	Investment cost, loading equipment	[€ million/jetty]	[1]				
	Investment cost, jetty	[€ million/jetty]	[1]				
	# of Jetty						
	Total Investment cost	[€ million]					
	Fixed OPEX rate	[%]	[1]				
	Fixed OPEX	[€/year]	[1]				
	scaling factor	[NA]	[2]				
	Lifetime	[years]	[1]				
Pipeline	Unloading flow rate	[ton/year]					
	Unloading flow rate	[m ³ /hr]					
	Pipeline length	[km]					
	pipeline diameter	[inch]					
	Pumping energy consumption	[kWh/kg]					
	Pipeline investment, specific	[€ million /km]	[1]				
	Pipeline investment	[€ million]					
	Fixed Opex rate	[%]					
	Fixed Opex	[€/year]					
	lifetime						
Total							
	Total import terminal investment cost	[€ million]					
	Total import terminal OPEX	[€ million/year]					

T4: LOHC (MCH)

T4: LOHC (MCH)							
Parameter name	Description	Unit	Source ID	Values/estimates			
				2020	2025	2030	2040
Import Terminal							
Jetty	Capacity	[ton/year]	[1]	4000000.00	4000000.0	4000000.0	4000000.0
	Call size of vessel	[ton]	[7]	115000	115000	115000	115000
	Vessel turnaround time	[hours]		36	36	36	36
	Berthing /Mooring time , tm	[hours]	[7]	28	28	28	28
	Unloading time, tu	[hours]	[7]	23	23	23	23
	Investment cost, loading equipment	[€ million/jetty]	[1]	1.00	1.0	1.0	1.0
	Investment cost, jetty	[€ million/jetty]	[1]	2.96	3.0	3.0	3.0
	# of Jetty			1.00	1.0	1.0	1.0
	Total Investment cost	[€ million]		3.96	4.0	4.0	4.0
	Fixed OPEX rate	[%]	[1]	2.0%	0.02	0.02	0.02
	Fixed OPEX	[€/year]	[1]	79200.00	79200	79200	79200
	scaling factor	[NA]	[2]	0.67	0.67	0.67	0.67
	Lifetime	[years]	[1]	30.00	30.0	30.0	30.0
Pipeline	Unloading flow rate	[ton/year]		4000000	4000000	4000000	4000000
	Unloading flow rate	[m ³ /hr]		7167.07	7167.066983	7167.067	7167.067
	Pipeline length	[km]		1	1	1	1
	pipeline diameter	[inch]		32	32	32	32
	Pumping energy consumption	[kWh/kg]		0	0.1	0.1	0.1
	Pipeline investment, specific	[€ million /km]	[1]	13.00	13	13	13
	Pipeline investment	[€ million]		13	13	13	13
	Fixed Opex rate	[%]	[1]	2.5%	0.025	0.025	0.025
	Fixed Opex	[€/year]		325,000	325000	325000	325000
	lifetime			26	26	26	26
Total							
	Total import terminal investment cost	[€ million]		51.96	52.0	52.0	52.0
	Total import terminal OPEX	[€ million/year]		1.10	1.1	1.1	1.1