## **TECHNOLOGY FACTSHEET**

## TNO

METHANOL PRODUCTIO											
	20-12-2019 Remko Detz										
Sector	Industry: Chemics										
, ·	ETS										
11 01	Production										
	In an exothermal reaction CO2 is hydrogenated with H2 to produce methanol, water, and heat. Some byproducts are formed and used as purge gas. This stream is finally combusted and emits CO2. The process runs at a typical temperature of 200-250 °C and at 30-80 bar. The conversion of CO2 in this direct methanol synthesis route is not so high (21%, Anicic, 2014; 33%, Van Dal, 2013), which allows for improvement in the future, e.g. by the development of new catalysts and technologies. After the reaction, the mixture is cooled and led through a flash separator/knock-out drum to separate the gasses from the liquid phase (crude methanol). The majority of the gasses (CO2 and CO) are recycled to the reactor. The										L%, Anicic, oled and led eactor. The
	crude methanol is purified by leading it through a fractionation column (connected to a heat exchanger) and a stripper unit. The process heat from the synthesis reactor generates steam, which is partly used in the purification process (fractionation and gas stripping) and may be used to generate electricity. Some electricity is required to run the plant, e.g. to drive the compressors for gas compression. The methanol plant is a net electricity consumer and steam producer. Both H2 and CO2 are provided in this case from external sources.										
	TRL 8 Conventional commercial scale methanol plants produce methanol from natural gas or coal (e.g. Lurgi Megamethanol process) at a scale of 3000-5000 ton per day, although via a syngas production step. CRI developed a direct hydrogenation process to convert CO2 with H2 into methanol (George Olah plant in Iceland 4000 ton/yr). The process is slightly different than conventional synthesis of methanol and further scale-up of the CRI plant has to be demonstrated (Marlin, 2018). For this reason we estimate the TRL at level 8.										
TECHNICAL DIMENSIONS	different than conventional synthes	sis of methanol	and further sca	lie-up of the CR	a plant has to t	e demonstrate	d (Marlin, 201	.8). For this reas	son we estimat	e the TRL at le	vel 8.
	Functional Unit					V	alue and Ran	ge			
Capacity	PJ		0.00			10.00			27.00		
	Global	PI		0.08			2030			37.00 <b>2050</b>	
Potential	Global	FJ		<b>Current</b> 100.00			1,432.68			8,643.88	
			0.08	-	2,000.00	1,432.68	-	1,432.68	8,643.88	-	8,643.88
Market share	Global	%	5.00	5.00	5.00	40.00	40.00	40.00	100.00	100.00	100.00
Capacity utlization factor			5.00		5.00	-0.00			1.00		100.00
Full-load running hours per year									8,322.00		
	PJ/year										
Technical lifetime (years)									25.00		
Progress ratio Hourly profile	No								0.90		
Explanation	The potentials are based on current	numbers for m	nethanol demai	nd We have nr	oiected future	demand for me	thanol by any	lving a linear g	rowth factor (D	etz et al 2019	8) starting
	from the current status and steadily road transport and shipping) is grov such as methanol-to-gasoline, meth CO2). The progress ratio is derived f faster than conventional methanol based on literature estimates.	ving. Total dem anol-to-olefins from Detz 2018	and in the futu , and methanol (methanol pla	re will depend -to-aromatics. nt), which migh	on its future ro We assume than It be conservat	ble and on the c at the process re ive as the direc	levelopment o uns 95% of the t hydrogenati	of conversion pr e time (based or on of CO2 is a ra	ocesses that us n continous sup ather novel tec	e methanol as oply facilities fo hnology and m	feedstock, or H2 and nay learn
	based of filefature estimates.										
COSTS	2015										
Year of Euro	Euro per Functional Ur	nit		•						2050	
				Current			2030			2050	
Investment costs	mln.€/ PJ			Current 11.00	22.00	7.00	<b>2030</b> 8.00	11.00	5.00	<b>2050</b> 7.00	44.00
	mln. € / PJ mln. € / PJ		3.00		23.00	7.00		11.00	5.00		11.00
Other costs per year	mln. € / PJ		3.00 Min	11.00 - - -	23.00 Max	<b>7.00</b> Min	8.00 - - -	11.00 Max	5.00 Min	7.00 - - -	11.00 Max
Other costs per year Fixed operational costs per year	mln. € / PJ mln. € / PJ			11.00 - -			8.00 - -			7.00 - -	
Other costs per year Fixed operational costs per year (excl. fuel costs)	mln. € / PJ		Min	11.00 - - 0.44	Max	Min	8.00 - - - 0.24	Мах	Min	7.00 - - -	Мах
Other costs per year Fixed operational costs per year (excl. fuel costs) Variable costs per year	mln. € / PJ mln. € / PJ		Min 0.09	11.00 - - 0.44 - -	Мах 0.92	Min 0.24	8.00 - - - 0.24 - -	<i>Max</i> 0.24	Min 0.18	7.00 - - -	Мах 0.18
Other costs per year Fixed operational costs per year (excl. fuel costs) Variable costs per year Costs explanation	mIn. € / PJ mIn. € / PJ mIn. € /		Min 0.09	11.00 - - 0.44 - - -	Мах 0.92	Min 0.24	8.00 - - 0.24 - - -	<i>Max</i> 0.24	Min 0.18	7.00 - - 0.18 - - -	Мах 0.18
Other costs per year Fixed operational costs per year (excl. fuel costs) Variable costs per year Costs explanation ENERGY IN- AND OUTPUTS	mIn. € / PJ mIn. € / PJ mIn. € / Energy carrier	Unit	Min 0.09	11.00 - - 0.44 - - - Current	Мах 0.92	Min 0.24	8.00 - - 0.24 - - - 2030	<i>Max</i> 0.24	Min 0.18	7.00 - - 0.18 - - - 2050	Мах 0.18
Other costs per year Fixed operational costs per year (excl. fuel costs) Variable costs per year Costs explanation ENERGY IN- AND OUTPUTS	mln. € / PJ mln. € / PJ mln. € / Energy carrier Main output:		Min 0.09 Min	11.00 0.44 1.22	Max 0.92 Max	Min 0.24 Min	8.00 - - 0.24 - - - - 2030 1.20	Max 0.24 Max	Min 0.18 Min	7.00 - - 0.18 - - - 2050 1.18	Max 0.18 Max
Other costs per year Fixed operational costs per year (excl. fuel costs) Variable costs per year Costs explanation ENERGY IN- AND OUTPUTS	mln. € / PJ mln. € / PJ mln. € / Energy carrier Main output: Hydrogen	Unit PJ	Min 0.09	11.00 - - 0.44 - - - Current	Мах 0.92	Min 0.24	8.00 - - 0.24 - - - 2030	<i>Max</i> 0.24	Min 0.18	7.00 - - 0.18 - - - 2050	Мах 0.18
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Other costs per year Fixed operational costs per year (excl. fuel costs) Variable costs per year Costs explanation ENERGY IN- AND OUTPUTS Energy carriers (per unit of main output)	mln. € / PJ mln. € / PJ mln. € / Energy carrier Main output: Hydrogen	Unit PJ	Min 0.09 Min 1.15 -1.00	11.00 - - 0.44 - - - - <b>Current</b> 1.22 - -1.00 - 0.05	Max 0.92 Max 1.25 -1.00	Min 0.24 Min 1.20 -1.00	8.00 - - 0.24 - - - - 2030 1.20 - -1.00 - 0.04	Max 0.24 Max 1.20 -1.00	Min 0.18 Min 1.18 -1.00	7.00 - - 0.18 - - - - 2050 1.18 - -1.00 - 0.03	Max 0.18 Max 1.18 -1.00
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Other costs per year Fixed operational costs per year (excl. fuel costs) Variable costs per year Costs explanation ENERGY IN- AND OUTPUTS Energy carriers (per unit of main output)	mln. € / PJ mln. € / PJ mln. € / Energy carrier Main output: Hydrogen Methanol	Unit PJ	Min 0.09 Min 1.15 -1.00	11.00 - - 0.44 - - - - <b>Current</b> 1.22 - -1.00 - 0.05	Max 0.92 Max 1.25 -1.00	Min 0.24 Min 1.20 -1.00	8.00 - - 0.24 - - - - 2030 1.20 - -1.00 - 0.04	Max 0.24 Max 1.20 -1.00	Min 0.18 Min 1.18 -1.00	7.00 - - 0.18 - - - - 2050 1.18 - -1.00 - 0.03	Max 0.18 Max 1.18 -1.00
Other costs per year Fixed operational costs per year (excl. fuel costs) Variable costs per year Costs explanation ENERGY IN- AND OUTPUTS Energy carriers (per unit of main output)	mln. € / PJ mln. € / PJ mln. € / PJ <u>Energy carrier</u> Main output: Hydrogen Methanol Electricity Heat The reaction between hydrogen and purification/distillation process. Ma literature. Here we take 92% conve	Unit PJ PJ PJ PJ d CO2 produces x energy efficie efficiency for 20	Min 0.09 Min 1.15 -1.00 0.03 -0.27 s methanol, wat ency is 89% at 1 020, which leads	11.00 - - 0.44 - - - - - - - - - - - - -	Max 0.92 Max 1.25 -1.00 0.06 0.09 mol H2 + 1 mo nversion efficie efficiency of 85	Min 0.24 Min 1.20 -1.00 0.04 -0.09 ol CO2 -> 1 mol ency. The carbo % or 1.22 PJ H2	8.00 - - 0.24 - - - - - - - - - - - - -	Max 0.24 Max 1.20 -1.00 0.04 -0.09 ol H2O + heat. The efficiency range	Min 0.18 Min 1.18 -1.00 0.03 -0.09 The heat is used es typically betw oduce 1 PJ of m	7.00 - - 0.18 - - - - - - - - - - - - -	Max 0.18 Max 1.18 1.18 -1.00 0.03 -0.09 9% in 09 PJ of heat.
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Other costs per year         Fixed operational costs per year         (excl. fuel costs)         Variable costs per year         Costs explanation         ENERGY IN- AND OUTPUTS         Energy carriers (per unit of main output)         Energy in- and Outputs explanation         MATERIAL FLOWS (OPTIONAL)	mIn. € / PJ mIn. € / PJ mIn. € / Energy carrier Main output: Hydrogen Methanol Electricity Heat The reaction between hydrogen and purification/distillation process. Ma literature. Here we take 92% conve Although the conversion efficiency i gas. This share is burned and provid and 0.01 PJ electricity produced). W 2020), while heat production remai	Unit PJ PJ PJ PJ d CO2 produces x energy efficies efficiency for 20 is high, the con les heat and CO /e assume that ns similar.	Min 0.09 Min 1.15 -1.00 0.03 -0.27 5 methanol, wat ency is 89% at 1 020, which leads version yield is 02 emissions. Additional contents of the second se	11.00 - - 0.44 - - - - - - - - - - - - -	Max 0.92 Max 1.25 -1.00 0.06 0.09 mol H2 + 1 mo nversion efficie efficiency of 85 to significant a icity for the pla	Min 0.24 Min 1.20 -1.00 0.04 -0.09 ol CO2 -> 1 mol ency. The carbo % or 1.22 PJ H2 amounts of recy ant ranges betw	8.00 - - 0.24 - - - - - - - - - - - - -	Max 0.24 Max 1.20 -1.00 0.04 -0.09 ol H2O + heat. The efficiency range electricity to pro- s. A small part of of which we se	Min 0.18 Min 1.18 -1.00 0.03 -0.09 The heat is used es typically betw oduce 1 PJ of m of the produced lect 0.05 PJ/PJ	7.00 - - 0.18 - - 0.18 - - - - - - - - - - - - -	Max         0.18         Max         1.18         -1.00         0.03         -0.09         9% in         09 PJ of heat.         ed as purge         PJ electricity in
Other costs per year         Fixed operational costs per year         (excl. fuel costs)         Variable costs per year         Costs explanation         ENERGY IN- AND OUTPUTS         Energy carriers (per unit of main output)         Energy in- and Outputs explanation         MATERIAL FLOWS (OPTIONAL)         Material flows	mIn. € / PJ mIn. € / PJ mIn. € / Main output: Hydrogen Methanol Electricity Heat The reaction between hydrogen and purification/distillation process. Ma literature. Here we take 92% conver Although the conversion efficiency i gas. This share is burned and provid and 0.01 PJ electricity produced). W 2020), while heat production remai	Unit         PJ         PJ         PJ         PJ         PJ         PJ         d CO2 produces         x energy efficie         efficiency for 20         is high, the con         les heat and CO         /e assume that         ns similar.         Unit         Mton/PJ         product         Mton/PJ	Min 0.09 Min 1.15 -1.00 0.03 -0.27 s methanol, wat ency is 89% at 1 020, which leads version yield is 02 emissions. Ac future plants b	11.00 - - 0.44 - - - - - - - - - - - - -	Max 0.92 Max 1.25 -1.00 0.06 0.09 mol H2 + 1 mon nversion efficient efficiency of 85 to significant a icity for the plat more efficient, 0.07	Min 0.24 Min 1.20 -1.00 0.04 -0.09 ol CO2 -> 1 mol ency. The carbo % or 1.22 PJ H2 amounts of recy ont ranges betw so we reduce H	8.00 - - - 0.24 - - - - - - - - - - - - -	Max 0.24 Max 1.20 1.20 -1.00 0.04 -0.09 ol H2O + heat. The efficiency range electricity to pro- s. A small part of of which we se electricity cons 0.07	Min 0.18 Min 1.18 1.18 -1.00 0.03 -0.09 The heat is used the produced lect 0.05 PJ/PJ umption (towa 0.07	7.00 - - 0.18 - - - - - - - - - - - - -	Max         0.18         Max         1.18         -1.00         0.03         -0.09         9% in         09 PJ of heat.         ed as purge         PJ electricity in         estimates of         0.07
Other costs per year         Fixed operational costs per year         (excl. fuel costs)         Variable costs per year         Costs explanation         ENERGY IN- AND OUTPUTS         Energy carriers (per unit of main output)         Energy in- and Outputs explanation         MATERIAL FLOWS (OPTIONAL)         Material flows         Material flows explanation	mIn. € / PJ mIn. € / PJ mIn. € / <b>Energy carrier</b> Main output: Hydrogen Methanol Electricity Heat The reaction between hydrogen and purification/distillation process. Ma literature. Here we take 92% convert Although the conversion efficiency is gas. This share is burned and provid and 0.01 PJ electricity produced). W 2020), while heat production remai	Unit PJ PJ PJ PJ CO2 produces and CO2 produces and CO2 produces beficiency for 20 bis high, the con bies heat and CO bis high, the con bies heat and CO bis high, the con bis similar. CO2 bis milar. CO2 bis milar. CO2 bis milar. CO2 bis milar. CO3 bis milar. CO3 bis milar. CO4	Min 0.09 Min 1.15 1.15 -1.00 0.03 -0.27 5 methanol, wat ency is 89% at 1 020, which leads version yield is 02 emissions. Ac future plants b 0.07 -0.03 5 methanol and d gas) are used	11.00 - - 0.44 - 0.44 - - 0.44 - - 0.44 - - 0.44 - - - - - - - - - - - - -	Max         0.92         Max         1.25         -1.00         0.06         0.09         mol H2 + 1 mol         nversion efficiency of 85         to significant a         icity for the playmore efficient,         0.07         -0.03         i2 + 1 mol CO2         his gas is used	Min $0.24$ Min $1.20$ $1.20$ $-1.00$ $0.04$ $0.04$ $0.04$ $0.04$ $0.04$ $0.04$ $0.04$ $0.07$ $0.07$ $-0.03$ $-> 1 \mod CH3O$	8.00 - - - 0.24 - - 0.24 - - - - - - - - - - - - -	Max 0.24 Max 1.20 1.20 -1.00 0.04 -0.09 ol H2O + heat. T efficiency range electricity to pro s. A small part of of which we se electricity cons 0.07 -0.03 0. Although the 12O and CO2 aft	Min 0.18 Min 1.18 1.18 -1.00 0.03 -0.09 The heat is used stypically betw oduce 1 PJ of m of the produced lect 0.05 PJ/PJ umption (towa 0.07 -0.03 conversion effi cer combustion	7.00 - - - 0.18 - - 0.18 - - - - - - - - - - - - -	Max         0.18         Max         1.18         -1.00         0.03         -0.09         9% in         09 PJ of heat.         ed as purge         PJ electricity in         estimates of         0.07         -0.03         we assume         rom air (also
Other costs per yearFixed operational costs per year (excl. fuel costs)Variable costs per yearCosts explanationENERGY IN- AND OUTPUTSEnergy carriers (per unit of main output)Energy in- and Outputs explanationMATERIAL FLOWS (OPTIONAL)Material flowsMaterial flows explanation	mln. € / PJ mln. € / PJ mln. € / Energy carrier Main output: Hydrogen Methanol Electricity Heat The reaction between hydrogen and purification/distillation process. Ma literature. Here we take 92% conver Although the conversion efficiency is gas. This share is burned and provid and 0.01 PJ electricity produced). W 2020), while heat production remai Material CO2 Water The reaction between hydrogen and that some of the gaseous byproduct pure oxygen can be used to burn th increases from 92% to 96%.	Unit         PJ         PJ         PJ         PJ         PJ         PJ         d CO2 produces         efficiency for 20         is high, the con         les heat and CO         /e assume that         ns similar.         Unit         Mton/PJ         product         Mton/PJ         product         d CO2 produces         is (or unreacted         e purge flows, or	Min 0.09 Min 1.15 1.15 -1.00 0.03 -0.27 5 methanol, wat ency is 89% at 1 020, which leads version yield is 02 emissions. Ac future plants b 0.07 -0.03 5 methanol and d gas) are used	11.00 - - 0.44 - 0.44 - - 0.44 - - 0.44 - - 0.44 - - - - - - - - - - - - -	Max         0.92         Max         1.25         -1.00         0.06         0.09         mol H2 + 1 mol         nversion efficiency of 85         to significant a         icity for the playmore efficient,         0.07         -0.03         i2 + 1 mol CO2         his gas is used	Min $0.24$ Min $1.20$ $1.20$ $-1.00$ $0.04$ $0.04$ $0.04$ $0.04$ $0.04$ $0.04$ $0.04$ $0.07$ $0.07$ $-0.03$ $-> 1 \mod CH3O$	8.00 - - - 0.24 - - 0.24 - - - - - - - - - - - - -	Max 0.24 Max 1.20 1.20 -1.00 0.04 -0.09 ol H2O + heat. T efficiency range electricity to pro s. A small part of of which we se electricity cons 0.07 -0.03 0. Although the 12O and CO2 aft	Min 0.18 Min 1.18 1.18 -1.00 0.03 -0.09 The heat is used stypically betw oduce 1 PJ of m of the produced lect 0.05 PJ/PJ umption (towa 0.07 -0.03 conversion effi cer combustion	7.00 - - - 0.18 - - 0.18 - - - - - - - - - - - - -	Max         0.18         Max         1.18         -1.00         0.03         -0.09         9% in         09 PJ of heat.         ed as purge         PJ electricity in         estimates of         0.07         -0.03         we assume         rom air (also
Other costs per year   Fixed operational costs per year   (excl. fuel costs)   Variable costs per year   Costs explanation   ENERGY IN- AND OUTPUTS   Energy carriers (per unit of main output)   Energy in- and Outputs explanation   MATERIAL FLOWS (OPTIONAL)   Material flows   Material flows explanation	mln. € / PJ mln. € / PJ mln. € / Energy carrier Main output: Hydrogen Methanol Electricity Heat The reaction between hydrogen and purification/distillation process. Ma literature. Here we take 92% conver Although the conversion efficiency is gas. This share is burned and provid and 0.01 PJ electricity produced). W 2020), while heat production remai Material CO2 Water The reaction between hydrogen and that some of the gaseous byproduct pure oxygen can be used to burn th increases from 92% to 96%.	Unit         PJ         PJ         PJ         PJ         PJ         PJ         d CO2 produces         efficiency for 20         is high, the con         les heat and CO         /e assume that         ns similar.         Unit         Mton/PJ         product         Mton/PJ         product         d CO2 produces         is (or unreacted         e purge flows, or	Min 0.09 Min 1.15 1.15 -1.00 0.03 -0.27 5 methanol, wat ency is 89% at 1 020, which leads version yield is 02 emissions. Ac future plants b 0.07 -0.03 5 methanol and d gas) are used	11.00 - - 0.44 - 0.44 - - 0.44 - - 0.44 - - 0.44 - - - - - - - - - - - - -	Max         0.92         Max         1.25         -1.00         0.06         0.09         mol H2 + 1 mol         nversion efficiency of 85         to significant a         icity for the playmore efficient,         0.07         -0.03         i2 + 1 mol CO2         his gas is used	Min $0.24$ Min $1.20$ $1.20$ $-1.00$ $0.04$ $0.04$ $0.04$ $0.04$ $0.04$ $0.04$ $0.04$ $0.07$ $0.07$ $-0.03$ $-> 1 \mod CH3O$	8.00 - - - 0.24 - - 0.24 - - - - - - - - - - - - -	Max 0.24 Max 1.20 1.20 -1.00 0.04 -0.09 ol H2O + heat. T efficiency range electricity to pro s. A small part of of which we se electricity cons 0.07 -0.03 0. Although the 12O and CO2 aft	Min 0.18 Min 1.18 1.18 -1.00 0.03 -0.09 The heat is used stypically betw oduce 1 PJ of m of the produced lect 0.05 PJ/PJ umption (towa 0.07 -0.03 conversion effi cer combustion	7.00 - - - 0.18 - - 0.18 - - - - - - - - - - - - -	Max         0.18         0.18         Max         1.18         -1.00         0.03         -0.09         9% in         .09 PJ of heat.         ed as purge         PJ electricity i         estimates of         0.07         -0.03         we assume         rom air (also
Other costs per year   Fixed operational costs per year   (excl. fuel costs)   Variable costs per year   Costs explanation   ENERGY IN- AND OUTPUTS   Energy carriers (per unit of main output)   Energy in- and Outputs explanation   MATERIAL FLOWS (OPTIONAL)   Material flows   Material flows explanation   EMISSIONS (Non-fuel/energy-related emergy	mIn. € / PJ mIn. € / PJ mIn. € / PJ mIn. € / Energy carrier Main output: Hydrogen Methanol Electricity Heat The reaction between hydrogen and purification/distillation process. Ma literature. Here we take 92% conve Although the conversion efficiency is gas. This share is burned and provid and 0.01 PJ electricity produced). W 2020), while heat production remai Material CO2 Water The reaction between hydrogen and that some of the gaseous byproduct pure oxygen can be used to burn th increases from 92% to 96%.	Unit PJ PJ PJ PJ PJ CO2 produces creation of the con les heat and CC les heat and CC les heat and CC les heat and CC les similar. Unit Mton/PJ product Mton/PJ product d CO2 produces ts (or unreacted e purge flows, or s. CCS)	Min 0.09 Min 1.15 -1.00 0.03 -0.27 s methanol, wat ency is 89% at 1 020, which leads version yield is 02 emissions. Ac future plants b 120, which leads version yield is 02 emissions. Ac future plants b 0.07 -0.03 s methanol and d gas) are used e.g. if coupled t	11.00 - - 0.44 - 0.44 - - 0.44 - - 0.44 - - - - - - - - - - - - -	Max         0.92         Max         1.25         -1.00         0.06         0.09         mol H2 + 1 mol         nversion efficiency of 85         to significant a         icity for the play         more efficient,         0.07         -0.03         12 + 1 mol CO2         his gas is used         Thanks to imp	Min $0.24$ Min $1.20$ $-1.00$ $0.04$ $-0.09$ $0l CO2 -> 1 mol$ ency. The carbo         % or $1.22$ PJ H2         amounts of recy         amounts of recy $0.04$ $0.07$ $0.07$ $-0.03$ $-> 1$ mol CH3O         energetically arroved process of	8.00 - - - 0.24 - - 0.24 - - - - - - - - - - - - -	Max 0.24 Max 1.20 1.20 -1.00 0.04 -0.09 ol H2O + heat. T efficiency range electricity to pro- s. A small part of of which we se electricity cons electricity cons 0.07 -0.03 0. Although the 12O and CO2 aft assume that the	Min 0.18 Min 1.18 1.18 -1.00 0.03 -0.09 The heat is used the produced lect 0.05 PJ/PJ umption (towa 0.07 -0.03 conversion effi cer combustion e carbon conve	7.00 - - - 0.18 - - 0.18 - - - 0.18 - - - - - - - - - - - - -	Max         0.18         Max         1.18         -1.00         0.03         -0.09         % in         09 PJ of heat.         ed as purge         PJ electricity i         estimates of         0.07         -0.03         we assume         rom air (also y also
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Other costs per year         Fixed operational costs per year         (excl. fuel costs)         Variable costs per year         Costs explanation         ENERGY IN- AND OUTPUTS         Energy carriers (per unit of main output)         Energy in- and Outputs explanation         MATERIAL FLOWS (OPTIONAL)         Material flows         Material flows explanation         EMISSIONS (Non-fuel/energy-related em	mln. € / PJ         mln. € / PJ         mln. € /         mln. € /         Main output:         Hydrogen         Methanol         Electricity         Heat         The reaction between hydrogen and purification/distillation process. Maliterature. Here we take 92% converted Although the conversion efficiency in gas. This share is burned and provide and 0.01 PJ electricity produced). W 2020), while heat production remained CO2         Water         The reaction between hydrogen and provide and provide and 0.01 PJ electricity produced). W 2020), while heat production remained and provide and 0.01 PJ electricity produced and provide and 0.01 PJ electricity produced and	Unit         PJ         CO2 produces         Si high, the con         les heat and CO         /e assume that         ns similar.         Unit         Mton/PJ         product         Mton/PJ         product         d CO2 produces         ts (or unreacted         e purge flows, or         g. CCS)         Unit	Min 0.09 Min 1.15 1.15 -1.00 0.03 -0.27 5 methanol, wat ency is 89% at 1 020, which leads version yield is 02 emissions. Ac future plants b 1020, which leads version yield is 02 emissions. Ac future plants b 0.07 -0.03 5 methanol and d gas) are used e.g. if coupled t	11.00 - - 0.44 - 0.44 - - 0.44 - - 0.44 - - - - - - - - - - - - -	Max         0.92         Max         1.25         -1.00         0.06         0.09         mol H2 + 1 mol         nversion efficient         efficiency of 85         to significant at at a significant at a sis significant at a	Min         0.24         Min         1.20         -1.00         0.04         -0.09         ol CO2 -> 1 mol         ency. The carboo         % or 1.22 PJ H2         amounts of recy         amounts of recy         amounts of recy         on 0.07         -0.03         -> 1 mol CH3O         energetically ar         roved process of         0.07	8.00 - - - 0.24 - - 0.24 - - - - - - - - - - - - -	Max 0.24 Max 1.20 1.20 -1.00 0.04 -0.09 ol H2O + heat. T efficiency range electricity to pro- s. A small part of of which we se electricity cons of which we se electricity cons 0.07 -0.03 0. Although the 12O and CO2 aft assume that the 0.07	Min 0.18 Min 1.18 1.18 -1.00 0.03 -0.09 The heat is used s typically betw oduce 1 PJ of m of the produced lect 0.05 PJ/PJ umption (towa 0.07 -0.03 conversion effi cer combustion e carbon conve	7.00 - - - 0.18 - - - - - - - - - - - - -	Max         0.18         Max         1.18         -1.00         0.03         -0.09         % in         09 PJ of heat.         ed as purge         PJ electricity in         estimates of         0.07         -0.03         we assume         rom air (also y also         0.07
Other costs per year         Fixed operational costs per year         (excl. fuel costs)         Variable costs per year         Costs explanation         ENERGY IN- AND OUTPUTS         Energy carriers (per unit of main output)         Energy in- and Outputs explanation         MATERIAL FLOWS (OPTIONAL)         Material flows         Material flows explanation         EMISSIONS (Non-fuel/energy-related em	mIn. € / PJ mIn. € / PJ mIn. € / mIn. € / Energy carrier Main output: Hydrogen Methanol Electricity Heat The reaction between hydrogen and purification/distillation process. Ma literature. Here we take 92% conve Although the conversion efficiency i gas. This share is burned and provid and 0.01 PJ electricity produced). W 2020), while heat production remai Material CO2 Water The reaction between hydrogen and that some of the gaseous byproduct pure oxygen can be used to burn th increases from 92% to 96%. missions or emissions reductions (e.§ Substance CO2	Unit         PJ         CO2 produces         x energy efficiency for 20 (is high, the con les heat and CO //e assume that ns similar.         Ve assume that ns similar.         Unit         Mton/PJ product         Mton/PJ product         Mton/PJ product         d CO2 produces         ts (or unreacted e purge flows, or end to the purge flows,	Min         0.09         Min         1.15         -1.00         0.03         -0.27         s methanol, wat         ency is 89% at 1         020, which leads         version yield is         22 emissions. Ac         future plants b         0.07         -0.03         s methanol and         dgas) are used         e.g. if coupled to         0.07         -0.03	11.00 - - 0.44 - 0.44 - - 0.44 - - 0.44 - - - - - - - - - - - - -	Max         0.92         Max         1.25         -1.00         0.09         mol H2 + 1 mol         nversion efficient         efficiency of 85         to significant at         icity for the plate         more efficient,         0.07         -0.03         12 + 1 mol CO2         his gas is used         Thanks to imp         0.07         -0.03	Min 0.24 Min 1.20 1.20 -1.00 0.04 -0.09 ol CO2 -> 1 mol ency. The carbo % or 1.22 PJ H2 amounts of recy ont ranges betw so we reduce H 0.07 -0.03 -> 1 mol CH3O energetically ar roved process of 0.07 -0.01	8.00 - - - 0.24 - - 0.24 - - 0.24 - - - - - - - - - - - - -	Max         0.24         Max         1.20         -1.00         0.04         -0.09         ol H2O + heat. Tefficiency range         electricity to prosider to of which we set electricity construction         0.07         -0.03         0.07         -0.03         0.07         -0.03         0.07         -0.03         0.07         -0.03         0.07         -0.03	Min 0.18 Min 1.18 1.18 -1.00 0.03 -0.09 The heat is used es typically betw oduce 1 PJ of m of the produced lect 0.05 PJ/PJ umption (towa 0.07 -0.03 conversion effi cer combustion e carbon conve	7.00 - - - 0.18 - - 0.18 - - - - - - - - - - - - -	Max         0.18         Max         1.18         -1.00         0.03         -0.09         % in         09 PJ of heat.         ed as purge         PJ electricity in         estimates of         0.07         -0.03         we assume         rom air (also y also         0.07         -0.00
Other costs per year         Fixed operational costs per year         (excl. fuel costs)         Variable costs per year         Costs explanation         ENERGY IN- AND OUTPUTS         Energy carriers (per unit of main output)         Energy in- and Outputs explanation         MATERIAL FLOWS (OPTIONAL)         Material flows         Material flows explanation         EMISSIONS (Non-fuel/energy-related em	mIn. € / PJ mIn. € / PJ mIn. € / mIn. € / Energy carrier Main output: Hydrogen Methanol Electricity Heat The reaction between hydrogen and purification/distillation process. Ma literature. Here we take 92% conve Although the conversion efficiency i gas. This share is burned and provid and 0.01 PJ electricity produced). W 2020), while heat production remai Material CO2 Water The reaction between hydrogen and that some of the gaseous byproduct pure oxygen can be used to burn th increases from 92% to 96%. missions or emissions reductions (e.§ Substance CO2	Unit         PJ         CO2 produces         x energy efficiency for 20 (is high, the con les heat and CO //e assume that ns similar.         Ve assume that ns similar.         Unit         Mton/PJ product         Mton/PJ product         Mton/PJ product         d CO2 produces         ts (or unreacted e purge flows, or end to the purge flows,	Min 0.09 Min 1.15 1.15 -1.00 0.03 -0.27 5 methanol, wat ency is 89% at 1 020, which leads version yield is 02 emissions. Ac future plants b 1020, which leads version yield is 02 emissions. Ac future plants b 0.07 -0.03 5 methanol and d gas) are used e.g. if coupled t	11.00 - - 0.44 - 0.44 - - 0.44 - - - - - - - - - - - - -	Max         0.92         Max         1.25         -1.00         0.06         0.09         mol H2 + 1 mol         nversion efficient         efficiency of 85         to significant at at a significant at a sis significant at a	Min         0.24         Min         1.20         -1.00         0.04         -0.09         ol CO2 -> 1 mol         ency. The carboo         % or 1.22 PJ H2         amounts of recy         amounts of recy         amounts of recy         on 0.07         -0.03         -> 1 mol CH3O         energetically ar         roved process of         0.07	8.00 - - - 0.24 - - 0.24 - - - - - - - - - - - - -	Max 0.24 Max 1.20 1.20 -1.00 0.04 -0.09 ol H2O + heat. T efficiency range electricity to pro- s. A small part of of which we se electricity cons of which we se electricity cons 0.07 -0.03 0. Although the 12O and CO2 aft assume that the 0.07	Min 0.18 Min 1.18 1.18 -1.00 0.03 -0.09 The heat is used s typically betw oduce 1 PJ of m of the produced lect 0.05 PJ/PJ umption (towa 0.07 -0.03 conversion effi cer combustion e carbon conve	7.00 - - - 0.18 - - 0.18 - - - - - - - - - - - - -	Max         0.18         Max         1.18         -1.00         0.03         -0.09         9% in         09 PJ of heat.         ed as purge         PJ electricity ir         estimates of         0.07         -0.03         we assume         rom air (also         y also
Other costs per year Fixed operational costs per year (excl. fuel costs) Variable costs per year Costs explanation ENERGY IN- AND OUTPUTS Energy carriers (per unit of main output) Energy in- and Outputs explanation MATERIAL FLOWS (OPTIONAL) Material flows Material flows explanation EMISSIONS (Non-fuel/energy-related em Emissions	mIn. € / PJ mIn. € / PJ mIn. € / mIn. € / Energy carrier Main output: Hydrogen Methanol Electricity Heat The reaction between hydrogen and purification/distillation process. Ma literature. Here we take 92% conve Although the conversion efficiency i gas. This share is burned and provid and 0.01 PJ electricity produced). W 2020), while heat production remai Material CO2 Water The reaction between hydrogen and that some of the gaseous byproduct pure oxygen can be used to burn th increases from 92% to 96%. missions or emissions reductions (e.§ Substance CO2	Unit         PJ         PJ         PJ         PJ         PJ         PJ         PJ         PJ         d CO2 produces         x energy efficiency for 20 is high, the con les heat and CO //e assume that ns similar.         Unit         Mton/PJ product         Mton/PJ product         Mton/PJ product         d CO2 produces         ts (or unreacted purge flows, or state)         g. CCS)         Unit         Mton         Mton	Min         0.09         Min         1.15         -1.00         0.03         -0.27         a methanol, wat         20, which leads         version yield is         2 emissions. Act         future plants b         0.07         -0.03         a methanol and         das) are used         e.g. if coupled to         0.07         -0.03         methanol and         das) are used         e.g. if coupled to         Min         Min	11.00 - - 0.44 - 0.44 - - - - - - - - - - - - -	Max         0.92         Max         1.25         -1.00         0.06         0.09         mol H2 + 1 mol         nversion efficiency of 85         to significant a         icity for the playmore efficient,         0.07         -0.03         12 + 1 mol CO2         his gas is used         Thanks to imp         0.07         -0.03         Max         Max	Min         0.24         Min         1.20         -1.00         -1.00         0.04         -0.09         ol CO2 -> 1 molency. The carboo         % or 1.22 PJ H2         amounts of recy         amounts of recy         amounts of recy         on 0.07         -0.03         -> 1 mol CH3O         energetically arroved process of         0.07         -0.03         -> 1 mol CH3O         energetically arroved process of         0.07         -0.01         Min         Min	8.00 - - - 0.24 - - 0.24 - - - - - - - - - - - - -	Max 0.24 Max 1.20 1.20 -1.00 0.04 -0.09 ol H2O + heat. T efficiency range electricity to pro- s. A small part of of which we se electricity cons 0 which we se electricity cons 0.07 -0.03 0.07 -0.03 0.07 -0.03 0.07 -0.01 Max Max	Min 0.18 Min 1.18 1.18 -1.00 0.03 -0.09 The heat is used es typically betw oduce 1 PJ of m of the produced lect 0.05 PJ/PJ umption (towa 0.07 -0.03 conversion effi cer combustion e carbon conve	7.00 - - - 0.18 - - 0.18 - - - - - - - - - - - - -	Max         0.18         Max         1.18         -1.00         0.03         -0.09         % in         09 PJ of heat.         ed as purge         PJ electricity in         estimates of         0.07         -0.03         we assume         rom air (also y also         0.07         -0.00

OTHER										
Parameter	Unit	Current			2030			2050		
		-			-			-		
		Min	-	Max	Min	-	Max	Min	-	Max
			-			-	-		-	
		Min	-	Max	Min	-	Max	Min	-	Max
			-	T		-	1		-	T
		Min	-	Max	Min	-	Max	Min	_	Max
		Min	-	Мах	Min	-	Мах	Min	-	Мах
Explanation		171111		IVIUX	101111		Ινιαλ	101111		IVIUX
REFERENCES AND SOURCES										
CRI plant: http://www.carbonrecycling.is										
Lurgi and AirLiquide company brochure c	of the MegaMethanol process, derived from: https:/	//www.engine	ering-airliquide	.com/lurgi-me	gamethanol					
Detz et al. 2018. The future of solar fuels	: when could they become competitive?									
Tremel et al. 2015. Techno-economic ana	alysis for the synthesis of liquid and gaseous fuels ba	ased on hydrog	gen production	via electrolysis						
Anicic et al. 2014. Comparison between t	wo methods of methanol production from carbon o	dioxide								
Bazzanella and Ausfelder 2017. Low carbo	on energy and feedstock for the European chemica	l industry								
IEA 2018. The Future of Petrochemicals -	Towards more sustainable plastics and fertilisers									
Terwel et al. 2018. Carbon neutral aviation	on with current engine technology: the take-off of s	ynthetic keros	ene productior	in the Netherl	ands					
Van Dal and Bouallou 2013. Design and si	imulation of a methanol production plant from CO2	hydrogenatio	n							
IEA 2019. The Future of Hydrogen (Assum	nptions Annex)									
Bellotti et al. 2017. Feasibility study of me Chem., 2018, 6:446	ethanol production plant from hydrogen and captu	red carbon dio	xide; Marlin, D	.S., Sarron, E., S	iigurbjörnsson,	O., Process Ad	dvantages of Dir	ect CO2 to Me	thanol Synthes	is. Front.