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CIMAC White Paper 3

Efficiencies and Maturities of (Net) Zero Carbon Fuel Pathways

From the Greenhouse Gas Strategy Group

The first edition of this CIMAC White Paper was approved by the members of the CIMAC Council at its meeting on November 19, 2020.

Introduction

The CIMAC White Paper 1 “*Production Pathways for Hydrogen with a Zero Carbon Footprint*” [13] and 2 “*Zero and Net Zero Carbon Fuel Options*” [14] outline the bigger picture of the current alternative fuel debate in maritime shipping and elaborate the different fuel pathways. With the aim of addressing different criteria of (net) zero carbon fuels, this White Paper 3 supports the previous White Papers by giving an overview of current and projected maturities and energy efficiencies of the discussed technologies and fuel pathways. CIMAC argues for a well-to-wake approach if assessing alternative fuels and respective policies in maritime shipping. In this context, energy efficiency of fuel pathways is a major factor to consider for assessing upstream greenhouse gas (GHG) emissions and energy consumption. This White Paper summarizes and consolidates figures on technology readiness levels (TRL) and energy efficiency of fuel pathways from well-to-tank as displayed in Figure 1. As in the previous papers, the focus is on production of (net) zero carbon fuels[1] based on renewable energy and direct air capture (DAC) of CO_2, while also considering hydrogen (H_2) production methods alternative to water electrolysis. In this White Paper, the time frames are indicative of the efficiency status at present, around 2030 and in the long run towards 2050.

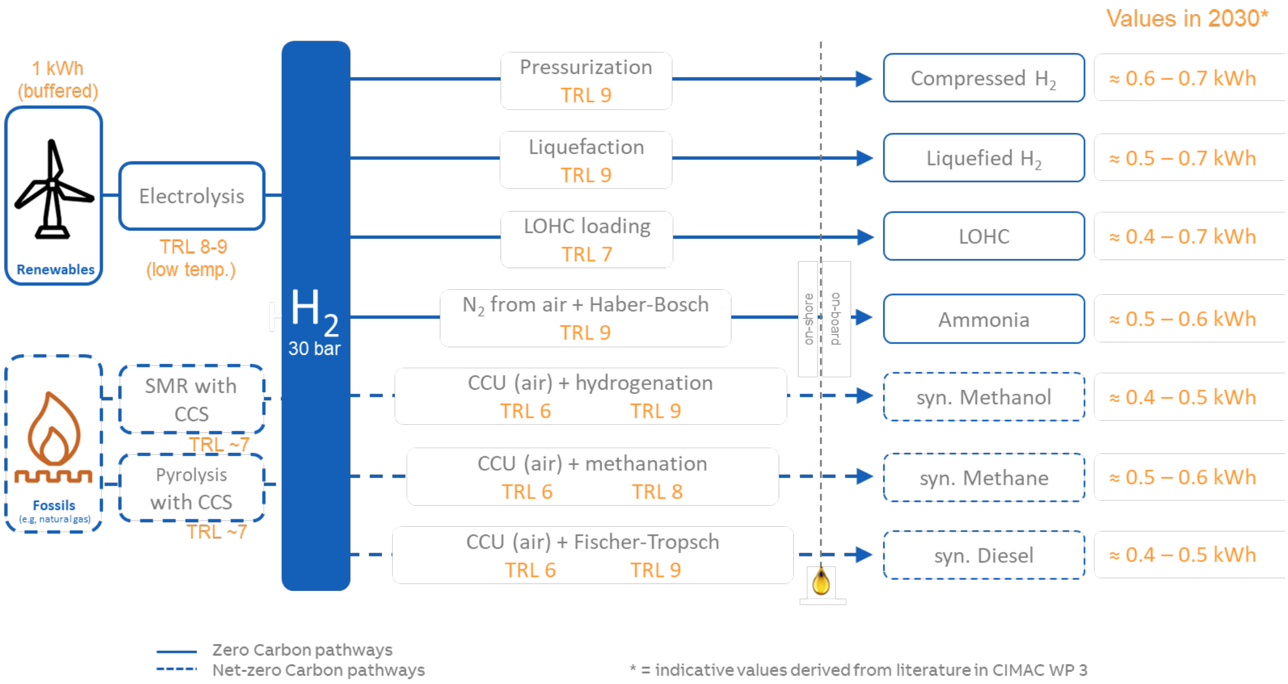

FIGURE 1 - (NET) ZERO CARBON FUEL PATHWAYS WITH STEPS AND RESOURCE INPUT; CCS= CARBON, CAPTURE AND STORAGE; SMR= STEAM METHANE REFORMING (SOURCE: ADAPTED FROM ABB, 2020)

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[1] As outlined by the Getting to Zero Coalition which CIMAC is supporting.

Hydrogen Production

Water electrolysis pathway / renewable pathway

The CIMAC White Paper 1 [13] already elaborates the different ways to produce hydrogen via water electrolysis. As can be seen in Table 1 and Table 2, the two technologies for low-temperature electrolysis, Alkali (ALK-EC) and proton exchange membrane (PEM-EC) electrolysis, are relatively similar in their efficiency and TRLs, but their applications differ. ALK-electrolysis is a well-established and the most wide-spread form of electrolysis for hydrogen production. ALK-electrolyzers are more suited for continuous operation, whereas PEM-electrolyzers can operate more flexibly and are more responsive. While solid oxide electrolyzers (SO-EC) and co-SO-EC offer the potential for higher efficiencies, there is the drawback of (currently) low maturity (Table 1 and Table 2) and lack of flexibility. Thus, most efficiency values for whole fuel pathways given in Table 2, Table 4 and Table 5 are based on low-temperature electrolysis.

As fresh water supply for water electrolysis is not sufficiently available everywhere, especially in regions with high solar energy potential, desalination of seawater might be necessary. The energy demand of a medium- to large-scale desalination plant is 3.1– 4.8 $kWh_{el}\ m^{-3}$ [2]. To fit the demands of water electrolysis, deionization of the water is required with an additional energy demand of 0.45 $kWh_{el}\ m^{-3}$ [4]. Compared to the water electrolysis, energy demand and costs of seawater desalination are negligible [4,12].

Depending on the further use and processes, the produced hydrogen needs to be liquefied, compressed, or attached to a hydrogen carrier (LOHC, ammonia). Efficiency values for these conversion steps are given in Table 2, and TRLs in Table 1.

TABLE 1 - TECHNOLOGY READINESS LEVELS (TRL) OF PROCESSES OF THE FUEL PATHWAYS (SOURCE: [4],[5],[8])

Process	TRL	Process	TRL
ALK-electrolysis	9	Direct Air Capture	6
PEM-electrolysis	8	Methanation (Sabatier)	8
SO-electrolysis	5-6	CH4 liquefaction	9
Co-SO-electrolysis	3-5	RWGS	6-7
H_2 liquefaction	9	Fischer-Tropsch	9
H_2 compression	9	Hydrocracking	9
LOHC	7	Methanol synthesis	9
H_2 storage	9	Haber-Bosch / Ammonia production	9

TABLE 2 - HYDROGEN PRODUCTION, PROCESS/PATHWAY EFFICIENCIES

Process	Pathway step	Efficiency in %	Year / time frame	Source
ALK-electrolysis	H_2 Production	65	Today	[1]
		58	2025	[4], LHV
		53-69	2030	[1], [9]
		61	2050	[4], LHV
PEM-electrolysis	H_2 Production	62-67	Today	[1]*, [2]***, [12] LHV
		58	2025	[4]*, LHV
		62.8 - 75.7	2030	[1]*, [9], [2]***, [12] LHV
		71-80	2050	[4]*, [12] LHV
SO-electrolysis	H_2 Production	81	Today	[12] LHV
		77-92	2030	[1], [9], [12] LHV
		90	2050	[12]
Co-SO-electrolysis	H_2 Production	81	2030	[1]
H_2 liquefaction	Conversion	79.7	Today	[2]
		83.7	2030	
H_2 compression	Conversion	94	Today	[11]
LOHC	Hydrogenation	100	Today	[2]**
	Dehydrogenation / Unloading	70	Today	[2]
		75	2030	
H_2 (compr.700 bar) via PEM	Whole chain / pathway	58	2030	[4]
		65	2050	
H_2 (compressed 250 bar) via ALK/PEM	Whole chain / pathway	61	Today	[3]
		70	2050	
H_2 (liquified) via ALK/PEM	Whole chain / pathway	53	Today	[3]
		64	2050	
H_2 (liquified.) via PEM, incl. transport via ship	Whole chain / pathway	52.4	2020	[2]
		57.9	2030	
H_2 (LOHC) via PEM, incl. transport via ship (heat either via H2 or external source)	Whole chain / pathway	42.6-49.2	2020	[2]
		60.8-65.6	2030	

* 5 MW PEM plant (90-100°C), **pressure fitted to PEM, *** 200-300 MW PEM, LHV= lower heating value

Alternative hydrogen production pathway / transition pathway

As outlined in CIMAC White Paper 1 [13] alternative hydrogen production pathways should be considered in view of limited renewable electricity and during a transitional phase for a large-scale supply of hydrogen. Hydrogen production through steam methane reforming (SMR) of natural gas is currently the most common hydrogen production way with a TRL of 9, whereas different forms of pyrolysis (thermal decomposition of carbon-based materials) have varying maturity levels (Table 3). The respective energy efficiencies of the combination of these two process with some form of carbon capture and storage (CCS) or carbon deposition are displayed in Table 3.

TABLE 3 - PYROLYSIS AND STEAM METHANE REFORMING

Process	Efficiency in %	Year / time frame	TRL	Source
SMR	70	Today	9	[6]
Pyrolysis	55	Today	Low-medium*	[7], [10]
SMR / Pyrolysis + CCS	56-65	Today	~7	[6], [10]

*depending on the type of pyrolysis covers different stages from R&D to commercially available processes

Ammonia production

For the ammonia synthesis, nitrogen (N_2) is captured from the air through cryogenic air separation and then fed into the well-established Haber-Bosch process with a TRL of 9 (Table 1). The efficiency for the whole fuel pathway (including the production of hydrogen through water electrolysis) is lower compared to the individual process steps of air separation or Haber-Bosch only (Table 4).

TABLE 4 - AMMONIA PRODUCTION

Process	Efficiency in %	Year / time frame	Source
Air separation	71.25	Today	[11]
Haber-Bosch	73.4-81.8	Today	[11]
Whole process incl. ALK/PEM, cryogenic air separation, Haber-Bosch	52 60	Today 2050	[3]
Whole process incl. PEM, cryogenic air separation, Haber-Bosch, compression and transport via ship	47.7 52.4	2020 2030	[2]

Carbon-based fuel pathways

Carbon-based synthetic fuels can be produced from hydrogen and carbon dioxide (CO_2) from renewable sources. DAC of CO_2 is considered herein. According to Hank et al. [2], 1.75 kWh thermal heat and 0.25 kWh electrical energy are needed for the capture of 1 kg of CO_2. Towards 2030, the energy demand might decrease to about 1.5 kWh_{th} and 0.2 kWh_{el}.

TABLE 5 - CARBON-BASED PROCESSES

Process	Pathway step	Efficiency in %	Year / time frame	Source
Methanation (catalytic)	Fuel synthesis	77-80	Today	[1],[12]
CH_4 liquefaction	Process step only	96.5	Today	[2]
		98.2	2030	
Methane (liqu.)	Whole chain, DAC, PEM	48	Today	[3]
	Whole chain, DAC, PEM, incl. transport via ship	43.9	Today	[2]
	Whole chain, DAC, PEM, incl. transport via ship	48.8	2030	[2]
	Whole chain, DAC, PEM	61	2050	[3]
Methane (gas.)	Whole chain, DAC, PEM	52	Today	[3]
		57	2050	
Diesel / Power-to-Liquid	Whole chain, DAC and ALK/PEM	45	Today	[3]
		38	2030	[4]
		53	2050	[3]
Fischer-Tropsch	Fuel synthesis	73-79.9	Today	[1],[12]
Methanol synthesis	Fuel synthesis	79-80.3	Today	[1],[11]
Methanol	Whole pathway, incl. DAC and ALK/PEM	40.2-45	Today	[2], [3]
		44.1	2030	[2]
		56	2050	[3]

Synthetic methane

Catalytic methanation (Sabatier process) and liquefaction (e.g. for transport) are well-developed (Table 1) with high efficiencies (Table 5). However, the efficiency for the whole methane (CH_4) fuel pathway is only at around 50% or less today.

Synthetic diesel

Like methane, the actual fuel synthesis of diesel (Fischer-Tropsch process) is a well-established process (Table 1). As a net zero carbon fuel, including DAC and green hydrogen, efficiency values for the fuel pathway are lower than for synthetic methane today and in future compared to the individual synthesis step of Fischer-Tropsch only (Table 5).

Synthetic methanol

Table 5 shows efficiency values for current industrial scale methanol synthesis (steps: production of syngas, production of crude-methanol and conditioning) as well as the efficiency of the fuel pathway based on hydrogen from water electrolysis. Currently, the efficiency of the methanol fuel pathway (incl. green hydrogen) is lower or equal compared to the diesel or methane fuel pathways (depending on system boundaries and source).

TABLE 6 - SUMMARY TABLE WITH A SIMPLIFIED COMPARISON OF THE FUEL PATHWAYS USING SIMILAR SOURCES

Fuel Pathway	Energy efficiency in %			Source
	Today	2030	2050	
Compressed H_2 (250bar)	61	-	70	[3]
Liquefied H_2	53	-	64	
LOHC	42.6-49.2	60.8-65.6	-	[2]
Ammonia	52	-	60	[3]
Methanol	40.2-45	-	56	
Methane (liqu.)	48	-	61	
Diesel	45	-	53	

Conclusion

Gains in fuel pathway efficiency are expected over time. As can be seen in Table 6, all fuel pathways' energy efficiencies will likely increase until 2050 (when comparing similar sources). However, the relative difference between the pathways will remain.

Synthesis and conditioning of synthetic fuels have a direct impact on the cost, as additional energy consumption for fuel production requires additional investment upfront and different pathways require different infrastructures. So, the evaluation of the potential of each fuel pathway should be done considering expected energy efficiency increases in future as well as time frames for investment. Surely, energy efficiency being only one factor for the assessment of future alternative fuels, it needs to be put in perspective with other aspects (like ease of handling, additional infrastructure investment, energy density and drop-in capability).

Electrolysis and hydrogen

PEM- and ALK-electrolysis are developed processes, but each have their advantages and disadvantages. The solid oxide electrolyzers (SO-EC) is still under development. Efficiency and TRL for SO-EC are projected to increase in the next decades. SO-EC being more efficient than PEM- and ALK-EC is thus a promising option to make the best use out of (so far limited) renewable energy. Considering that investments regarding the production of (net) zero carbon fuels should be made soon, the PEM-EC seems a viable option with high TRL, comparable good efficiencies and a flexible operation mode.

Handling of hydrogen onshore (liquefaction, storage etc.) is well-developed and thus a good basis for (net) zero carbon fuel production. However, handling and production of hydrogen are energy-intense. This is a bottleneck for fuel production, as all (net) zero carbon fuels rely on green hydrogen production, but the supply of renewable energy is yet limited and will remain most presumably low without a regulatory framework ensuring phasing out fossil-based hydrocarbons. Around 2030, the whole hydrogen fuel pathway (incl. transport via ship) could be at an efficiency of around 60%, depending on the storage or transportation form of hydrogen. Higher efficiencies are expected towards 2050, especially for compressed hydrogen.

Alternative hydrogen production

To enable a faster reduction of GHG emissions, the production of hydrogen from natural gas with CCS poses an alternative and should not be excluded. While steam methane reforming (SMR) is a mature and established process, pyrolysis is viewed as very promising but is at different stages of TRL (depending on the type of pyrolysis). However, these two options are only valid if they produce hydrogen with a lower carbon footprint than conventional (SMR) production methods. The necessary application of CCS lowers the TRL and efficiency of the SMR process, while pyrolysis does not need CO_2 capture as it produces pure carbon. Yet, current pyrolysis facilities are still small and have to prove that they can be expanded to large industrial scale. All these issues need to be considered when evaluating alternative fuels from SMR or pyrolysis pathways and when comparing these with other pathways based on renewable energy only.

Ammonia

Current (fossil-based) ammonia production itself is a developed large-scale process with relatively high fuel pathway efficiencies. However, through the production of hydrogen through water electrolysis and considering subsequent compression and transport of ammonia, it is expected that the ammonia fuel pathway will have a slightly lower fuel pathway efficiency compared to transportable hydrogen (compressed or liquefied see point above), but a higher fuel pathway efficiency than carbon-based synthetic fuels and current estimates provide that this will be continuing up for around 2050. Expected efficiency gains until 2050 depend mainly on improvements of water electrolysis.

Carbon-based fuels

DAC is still under development, but it is expected to have an energy demand of 1.5 kWh_{th} and 0.2 kWh_{el} in 2030. Comparing the overall efficiency of the carbon-based fuel pathways (incl. PEM and possible subsequent handling of the fuel like liquefaction or hydrocracking), efficiencies vary. All fuel pathway efficiencies are expected to increase from today to 2030 and further to 2050. In 2030, methanol and diesel are expected to have slightly lower overall efficiency than liquefied or compressed methane. In 2050, methane (gas.), diesel and methanol fuel pathway might increase their efficiency to more than 50%. Liquefied methane might be produced with an overall efficiency of around 60% in 2050.

Main take-aways

The production of (net) zero carbon fuels will become more efficient and further developed in the future, but differences in efficiency between fuel pathways will remain. These distinctions will be the main driver for alterations in price of the upcoming sustainable fuel choices. Today and towards 2030, carbon-free fuel pathways will likely reach higher efficiencies than carbon-based e-fuel pathways. The latter will reach efficiency levels comparable to hydrogen (in 2030) only towards 2050. While these developments are of course subject to uncertainty, many investments and larger projects need to be started soon (and likely based on current technologies) to produce sufficient (net) zero carbon fuels for an early uptake starting in the 2030s. Meanwhile, each additional energy consumption for fuel production right now requires additional upstream investments and thus impacts the investment decision.

However, fuel pathway efficiency and TRL are not the only factors to consider when evaluating and investing in (net) zero carbon fuels. This White Paper looks at the efficiencies from well-to-tank only. Measuring the real impact on GHG emissions requires a well-to-wake approach and thus include the production pathway up to the end including the onboard GHG impact from the vessel. Additionally, other factors like price, fuel availability or sustainability issues are important too, but are not within the scope of this White Paper.

Sources

[1] Brynolf et al. (2018) – Electrofuels for the transport sector : A review of production costs

[2] Hank et al. (2020) – Energy efficiency and economic assessment of imported energy carriers based on renewable electricity

[3] Öko Institut (2019) – Die Bedeutung strombasierter Stoffe für den Klimaschutz in Deutschland

[4] Töpler and Lehmann (2017) – Wasserstoff und Brennstoffzelle

[5] VDMA (2020) – Position Paper

[6] The Royal Society (2018) – Options for producing low-carbon hydrogen at scale

[7] Weger et al. (2017) – Methane cracking as a bridge technology to the hydrogen economy

[8] 42Technology

[9] FCH JU (2015) - Commercialisation of energy storage in Europe

[10] Timmerberg et al. (2020) - Hydrogen and hydrogen-derived fuels through methane decomposition of natural gas - GHG emissions and costs

[11] Llyods‘ Register/UMAS (2019) - Fuel production cost estimates and assumptions

[12] Agora Energiewende / Agora Verkehrswende – The future cost of electricity-based synthetic fuels

[13] CIMAC (2020) - White Paper 1: Production Pathways for Hydrogen with a Zero Carbon Footprint

[14] CIMAC (2020) - White Paper 2: Zero and Net Zero Carbon Fuel Options

Imprint

CIMAC e. V.
Lyoner Strasse 18
60528 Frankfurt
Germany

President: Prof. Dr. Donghan, Jin
Secretary General: Peter Müller-Baum

Phone +49 69 6603-1567
E-mail: info@cimac.com

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