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Economic analysis of hydrogen production in Germany with a focus on green hydrogen, considering all three major water electrolysis technologies

14 pages, 0 figures, 11 tables

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S.1 Water electrolysis technologies

Water electrolysis is a well-known electrochemical reaction where H_2O is split into its original components H_2 and O_2 (see Eq. 1). This occurs at the cathode and anode, with hydrogen forming at the negatively charged cathode and oxygen at the positively charged anode. [1]. The most significant technologies for this process are AEL, PEM, and SOEC. These technologies differentiate regarding the charge carrier, amongst other things. In this regard, the charge carrier for AEL is OH^-, for PEM is H_3O^+/H^+, and for SOEC is O^{2-} [2].

Moreover, these technologies can help to mitigate climate change if renewable energy is considered for green hydrogen production. Then, CO_2 emission can be reduced significantly if green hydrogen is used to replace fossil-based hydrogen. The reason is that more than 90% of the world's hydrogen is produced by steam reforming (grey hydrogen) and therefore natural gas, thus leading to tremendous CO_2 emissions [3]. Consequently, grey hydrogen can be replaced sustainably by green hydrogen [4,5]. Besides that, the technologies have different advantages and disadvantages and differentiate regarding efficiency, lifetime, and technology readiness level, among other things. Table 1 shows an overview.

$$H_2O \rightarrow H_2 + 0.5\,O_2 \quad \text{Eq.1}$$

Table 1: Overview of main characteristics [4-6]

	AEL	PEM	SOEC
Electrolyte	NaOH, KOH	Solid Polymer	Yttria-stabilized zirconium oxide
Electrodes	Ni	Pt/C/IrO2	Ni, ceramic
System lifetime (years)	20-30	20-30	20
Temperature °C	60-80	50-80	800-1000
Pressure bar	1-15	1-50	1-5
Efficiency %	65-75	50-75	80-90
Cold start up (min)	15	<15	<60
Power density (W/cm^2)	Up to 1	Up to 4.4	65-70
Stage of development	Commercial	Early commercialisation	Early Development
Technology readiness level (TRL)	9	7-8	5-7
Advantages	Low material costs, large plant size	Flexibility, faster cold start	High efficiency, usage of waste heat
Disadvantages	Low current density, high maintenance costs	Use of noble materials, low electrolyte/electrode durability	Constant operation, short-term stability

1.2.2 Alkaline electrolysis (AEL)

The AEL technology is commercially available since decades. This technology is available for large plant sizes and has a lifetime of approx. 20 to 30 years. The process operates at levels of between 60 and 80°C at 1-15 bar and has a process efficiency between 65-75%, while the cold start up time is approx. 15 min and the power density is up to 1 W/cm^2. Besides that, sodium and potassium hydroxide are commonly used as an electrolyte. The use of non-noble materials and therefore relatively cheap material costs is the main advantage of the AEL technology, whereby corrosion –sodium and potassium hydroxide are commonly used as an electrolyte– and therefore high maintenance costs as well as a low current density are the main disadvantages of the technology [4-6].

1.2.3 Polymer electrolyte membrane (PEM)

The technology's first draft was designed in the 1950s by Grubb and further evolved in the 1960s by General Electric. The PEM technology is at an early commercialisation stage and has a system lifetime of 20-30 years, according to [26]. The process operates at temperatures between 50 to 80°C at 1-50 bar and has an efficiency of approx. 50-75%, while the cold start up time is below 15 min and the power density is up to 4.4 W/cm^2. Compared to AEL, PEM has a higher flexibility and faster cold start and utilises a solid polymeric membrane instead of a liquid electrolyte and is thus not affected by corrosion. However, the technology uses noble materials, such as iridium, that leads to higher material costs and is therefore disadvantageous compared to the AEL technology. A replacement of iridium by a non-noble metal would considerably reduce the material costs and considered as a breakthrough [4-6].

1.2.4 Solid oxide electrolysis cell (SOEC)

The technology readiness level (TRL) of the SOEC technology is in between 5-7 and is therefore still on an early stage of development. The process operates at high temperature levels of 800–1000 °C at 1-5 bar and has a significantly higher efficiency compared to AEL and PEM (80-90%), while the cold start up time and power density lie below 60 min and between 65-70 W/cm^2, respectively. Besides that, yttria-stabilized zirconium oxide is used as an electrolyte. The process needs to be in constant operation. Otherwise, heat losses will occur and reduce the cell temperature considerably with the consequence of micro-cracks in the membrane. On the other side, material decomposition occurs due to high temperatures that leads to short-term stability. For a secure and stable operation in the future, these challenges need to be solved sustainably [4-6].

1.2.5 Blue and grey hydrogen

The terms blue and grey hydrogen refer to the production of hydrogen from fossil fuels, predominantly using natural gas. The difference between blue and grey hydrogen is that the CO_2 emissions released during the production of blue hydrogen are stored and thus not emitted into the atmosphere, whereas the CO_2 emissions during the production of grey hydrogen are released directly into the atmosphere. For this reason, blue hydrogen is more expensive to produce at about 2 €/kg H_2 than grey hydrogen (1.5 €/kg H_2) [5]. The prices refer to natural gas prices from before the war.

More information with regard to the electrolysis technologies can be found here [2,4].

S.2 Results of LCOH in absolute figures

Table 2: Results of LCOH for 10 MW plants

		4000h	4000h_RE	6000h	8000h
current	AEL	14.43	5.00	13.62	13.30
	PEM	15.00	5.18	14.45	13.97
	SOEC	13.66	5.96	12.56	11.97
2030	AEL	5.84	3.72	5.38	5.18
	PEM	6.09	3.74	5.70	5.55
	SOEC	4.97	3.27	4.49	4.26
2050	AEL	5.54	2.92	5.32	5.19
	PEM	5.42	2.73	5.25	5.17
	SOEC	4.47	2.39	4.24	4.11

Table 3: Results of LCOH for 100 MW plants

		4000h	4000h_RE	6000h	8000h
current	AEL	13.88	4.44	13.24	12.98
	PEM	14.52	4.69	14.06	13.67
	SOEC	12.33	4.63	11.59	11.19
2030	AEL	5.45	3.33	5.11	4.97
	PEM	5.73	3.38	5.46	5.35
	SOEC	4.38	2.68	4.09	3.94
2050	AEL	5.27	2.65	5.13	5.05
	PEM	5.31	2.62	5.17	5.11
	SOEC	4.12	2.04	4.00	3.93

S.3 Results with/without electricity costs and changes

Table 4: Results with/without electricity costs for 10 MW plants

		4000h	4000h_0_€/MWh	4000h_RE	4000h_RE_0_€/MWh	6000h	6000h_0_€/MWh	8000h	8000h_0_€/MWh
current	AEL	14.43	2.41	5.00	2.41	13.62	1.60	13.30	1.27
	PEM	15.00	2.48	5.18	2.48	14.45	1.93	13.97	1.45
	SOEC	13.66	3.84	5.96	3.84	12.56	2.74	11.97	2.15
2030	AEL	5.84	1.25	3.72	1.25	5.38	0.80	5.18	0.60
	PEM	6.09	1.00	3.74	1.00	5.70	0.62	5.55	0.47
	SOEC	4.97	1.29	3.27	1.29	4.49	0.82	4.26	0.58
2050	AEL	5.54	0.53	2.92	0.53	5.32	0.31	5.19	0.18
	PEM	5.42	0.28	2.73	0.28	5.25	0.11	5.17	0.03
	SOEC	4.47	0.50	2.39	0.50	4.24	0.26	4.11	0.14

Table 5: Results with/without electricity costs for 100 MW plants

		4000h	4000h_0_€/MWh	4000h_RE	4000h_RE_0_€/MWh	6000h	6000h_0_€/MWh	8000h	8000h_0_€/MWh
current	AEL	13.88	1.85	4.44	1.85	13.24	1.21	12.98	0.95
	PEM	14.52	2.00	4.69	2.00	14.06	1.54	13.67	1.15
	SOEC	12.33	2.51	4.63	2.51	11.59	1.77	11.19	1.37
2030	AEL	5.45	0.87	3.33	0.87	5.11	0.53	4.97	0.38
	PEM	5.73	0.65	3.38	0.65	5.46	0.38	5.35	0.27
	SOEC	4.38	0.71	2.68	0.71	4.09	0.41	3.94	0.27
2050	AEL	5.27	0.27	2.65	0.27	5.13	0.12	5.05	0.04
	PEM	5.31	0.17	2.62	0.17	5.17	0.03	5.11	-0.03
	SOEC	4.12	0.15	2.04	0.15	4.00	0.02	3.93	-0.04

Table 6: Changes when electricity price is 0 € (10 MW)

		4000h	4000h_RE	6000h	8000h
current	AEL	83.3%	51.8%	88.3%	90.5%
	PEM	83.5%	52.1%	86.7%	89.6%
	SOEC	71.9%	35.5%	78.2%	82.1%
2030	AEL	78.5%	66.3%	85.2%	88.4%
	PEM	83.5%	73.1%	89.1%	91.6%
	SOEC	74.0%	60.4%	81.8%	86.4%
2050	AEL	90.4%	81.7%	94.2%	96.4%
	PEM	94.8%	89.8%	98.0%	99.4%
	SOEC	88.8%	79.1%	93.8%	96.6%

Table 7: Changes when electricity price is 0 € (100 MW)

		4000h	4000h_RE	6000h	8000h
current	AEL	86.7%	58.3%	90.9%	92.7%
	PEM	86.3%	57.5%	89.0%	91.6%
	SOEC	79.6%	45.7%	84.8%	87.8%
2030	AEL	84.1%	74.0%	89.7%	92.3%
	PEM	88.7%	80.8%	93.1%	95.0%
	SOEC	83.9%	73.7%	89.9%	93.3%
2050	AEL	95.0%	90.0%	97.7%	99.3%
	PEM	96.8%	93.6%	99.4%	n/a
	SOEC	96.4%	92.8%	99.5%	n/a

S.4 Results of Sensitivity analysis

Table 8: Sensitivity analysis: CAPEX 10 and 100 MW

	CAPEX_10 MW								
+20%	Current			2030			2050		
Current	AEL	PEM	SOEC	AEL	PEM	SOEC	AEL	PEM	SOEC
4000h	3%	3%	4%	4%	3%	5%	2%	2%	3%
4000_RE	8%	8%	10%	6%	5%	7%	3%	2%	3%
6000h	2%	2%	3%	3%	2%	4%	2%	1%	2%
8000h	1%	1%	2%	2%	2%	3%	1%	1%	2%
	CAPEX								
-20%	Current			2030			2050		
Current	AEL	PEM	SOEC	AEL	PEM	SOEC	AEL	PEM	SOEC
4000h	-3%	-3%	-4%	-4%	-3%	-5%	-2%	-2%	-3%
4000_RE	-8%	-8%	-10%	-6%	-5%	-7%	-3%	-2%	-3%
6000h	-2%	-2%	-3%	-3%	-2%	-4%	-2%	-1%	-2%
8000h	-1%	-1%	-2%	-2%	-2%	-3%	-1%	-1%	-2%
	CAPEX_100 MW								
+20%	Current			2030			2050		
2030	AEL	PEM	SOEC	AEL	PEM	SOEC	AEL	PEM	SOEC
4000h	2%	2%	3%	3%	2%	3%	2%	1%	2%
4000_RE	7%	7%	8%	5%	4%	6%	3%	3%	3%
6000h	2%	2%	2%	2%	2%	2%	1%	1%	1%
8000h	1%	1%	2%	2%	1%	2%	1%	1%	1%
	CAPEX								
-20%	Current			2030			2050		
2030	AEL	PEM	SOEC	AEL	PEM	SOEC	AEL	PEM	SOEC
4000h	-2%	-2%	-3%	-3%	-2%	-3%	-2%	-1%	-2%
4000_RE	-7%	-7%	-8%	-5%	-4%	-6%	-3%	-3%	-3%
6000h	-2%	-2%	-2%	-2%	-2%	-2%	-1%	-1%	-1%
8000h	-1%	-1%	-2%	-2%	-1%	-2%	-1%	-1%	-1%

Table 9: Sensitivity analysis: Discount rate 10 and 100 MW

	Discount rate_10 MW								
+20%	Current			2030			2050		
Current	AEL	PEM	SOEC	AEL	PEM	SOEC	AEL	PEM	SOEC
4000h	2%	2%	3%	3%	2%	3%	2%	1%	2%
4000_RE	5%	5%	7%	4%	3%	5%	5%	5%	5%
6000h	1%	1%	2%	2%	1%	2%	1%	1%	1%
8000h	1%	1%	2%	1%	1%	2%	1%	1%	1%
	Discount rate								
-20%	Current			2030			2050		
Current	AEL	PEM	SOEC	AEL	PEM	SOEC	AEL	PEM	SOEC
4000h	-2%	-2%	-3%	-2%	-2%	-3%	-2%	-1%	-2%
4000_RE	-5%	-5%	-6%	-4%	-3%	-5%	-5%	-5%	-4%
6000h	-1%	-1%	-2%	-2%	-1%	-2%	-1%	-1%	-1%
8000h	-1%	-1%	-2%	-1%	-1%	-2%	-1%	-1%	-1%
	Discount rate_100 MW								
+20%	Current			2030			2050		
2030	AEL	PEM	SOEC	AEL	PEM	SOEC	AEL	PEM	SOEC
4000h	1%	1%	2%	1%	1%	1%	1%	1%	1%
4000_RE	5%	4%	6%	4%	4%	4%	2%	2%	2%
6000h	1%	1%	2%	1%	1%	1%	1%	1%	1%
8000h	1%	1%	1%	1%	1%	1%	1%	0%	1%
	Discount rate								
-20%	Current			2030			2050		
2030	AEL	PEM	SOEC	AEL	PEM	SOEC	AEL	PEM	SOEC
4000h	-1%	-1%	-2%	-1%	-1%	-1%	-1%	-1%	-1%
4000_RE	-4%	-4%	-6%	-4%	-4%	-4%	-2%	-2%	-2%
6000h	-1%	-1%	-1%	-1%	-1%	-1%	-1%	-1%	-1%
8000h	-1%	-1%	-1%	-1%	-1%	-1%	-1%	0%	-1%

Table 10: Sensitivity analysis: Electricity price 10 and 100 MW

	Electricity_10 MW								
+20%	Current			2030			2050		
Current	AEL	PEM	SOEC	AEL	PEM	SOEC	AEL	PEM	SOEC
4000h	17%	17%	14%	16%	17%	15%	18%	19%	18%
4000_RE	10%	10%	7%	13%	15%	12%	19%	20%	19%
6000h	18%	17%	16%	17%	18%	16%	19%	20%	19%
8000h	18%	18%	16%	18%	18%	17%	19%	20%	19%
	Electricity								
-20%	Current			2030			2050		
Current	AEL	PEM	SOEC	AEL	PEM	SOEC	AEL	PEM	SOEC
4000h	-17%	-17%	-14%	-16%	-17%	-15%	-18%	-19%	-18%
4000_RE	-10%	-10%	-7%	-13%	-15%	-12%	-19%	-20%	-19%
6000h	-18%	-17%	-16%	-17%	-18%	-16%	-19%	-20%	-19%
8000h	-18%	-18%	-16%	-18%	-18%	-17%	-19%	-20%	-19%
	Electricity_100 MW								
+20%	Current			2030			2050		
2030	AEL	PEM	SOEC	AEL	PEM	SOEC	AEL	PEM	SOEC
4000h	17%	17%	16%	17%	18%	17%	19%	19%	19%
4000_RE	12%	11%	9%	15%	16%	15%	18%	19%	19%
6000h	18%	18%	17%	18%	19%	18%	20%	20%	20%
8000h	19%	18%	18%	18%	19%	19%	20%	20%	20%
	Electricity								
-20%	Current			2030			2050		
2030	AEL	PEM	SOEC	AEL	PEM	SOEC	AEL	PEM	SOEC
4000h	-17%	-17%	-16%	-17%	-18%	-17%	-19%	-19%	-19%
4000_RE	-12%	-11%	-9%	-15%	-16%	-15%	-18%	-19%	-19%
6000h	-18%	-18%	-17%	-18%	-19%	-18%	-20%	-20%	-20%
8000h	-19%	-18%	-18%	-18%	-19%	-19%	-20%	-20%	-20%

Table 11: Sensitivity analysis: Efficiency 10 and 100 MW

	Efficiency_10 MW								
+20%	Current			2030			2050		
Current	AEL	PEM	SOEC	AEL	PEM	SOEC	AEL	PEM	SOEC
4000h	-17%	-17%	-17%	-17%	-17%	-17%	-17%	-17%	-17%
4000_RE	-17%	-17%	-17%	-17%	-17%	-17%	-17%	-17%	-17%
6000h	-17%	-17%	-17%	-17%	-17%	-17%	-17%	-17%	-17%
8000h	-17%	-17%	-17%	-17%	-17%	-17%	-17%	-17%	-17%
	Efficiency								
-20%	Current			2030			2050		
Current	AEL	PEM	SOEC	AEL	PEM	SOEC	AEL	PEM	SOEC
4000h	25%	25%	25%	25%	25%	25%	25%	25%	25%
4000_RE	25%	25%	25%	25%	25%	25%	25%	25%	25%
6000h	25%	25%	25%	25%	25%	25%	25%	25%	25%
8000h	25%	25%	25%	25%	25%	25%	25%	25%	25%
	Efficiency_100 MW								
+20%	Current			2030			2050		
2030	AEL	PEM	SOEC	AEL	PEM	SOEC	AEL	PEM	SOEC
4000h	-17%	-17%	-17%	-17%	-17%	-17%	-17%	-17%	-17%
4000_RE	-17%	-17%	-17%	-17%	-17%	-17%	-17%	-17%	-17%
6000h	-17%	-17%	-17%	-17%	-17%	-17%	-17%	-17%	-17%
8000h	-17%	-17%	-17%	-17%	-17%	-17%	-17%	-17%	-17%
	Efficiency								
-20%	Current			2030			2050		
2030	AEL	PEM	SOEC	AEL	PEM	SOEC	AEL	PEM	SOEC
4000h	25%	25%	25%	25%	25%	25%	25%	25%	25%
4000_RE	25%	25%	25%	25%	25%	25%	25%	25%	25%
6000h	25%	25%	25%	25%	25%	25%	25%	25%	25%
8000h	25%	25%	25%	25%	25%	25%	25%	25%	25%

S.5 References

[1] Kumar Shiva, S., Himabindu, V. Hydrogen production by PEM water electrolysis – A review. *Mat. Sci. Energy Technol*. 2019, 2, 442–454. https://doi.org/10.1016/j.mset.2019.03.002.

[2] Götz, M.; Lefebvre, J.; Mörs, F.; McDaniel Koch, A.; Graf, F.; Bajohr, S.; Reimert, R.; Kolb, T. Renewable Power-to-Gas: A technological and economic review. *Renew. Energ*. 2016, 85, 1371–1390. DOI 10.1016/j.renene.2015.07.066

[3] Rapier, R. *Estimating the Carbon Footprint of Hydrogen.* https://www.forbes.com/sites/mitsubishiheavyindustries/2022/01/26/the-stark-difference-between-global-warming-of-15c-and-20c/?sh=3f7ba7f02a48 (accessed Dec 11, 2022).

[4] Dahiru, A.R., Vuokila, A., Huuhtanen, M. Recent development in Power-to-X: Part I – A review on techno-economic analysis. *J. Energy Storage.* 2022, 56, 105861 DOI.10.1016/j.est.2022.105861

[5] Horng, P., Kalis, M. *Wasserstoff - Farbenlehre. Rechtswissenschaftliche und rechtspolitische Kurzstudie*. Institut für Klimaschutz, Energie und Mobilität e.V. (IKEM) (Ed.), 2020. https://www.ikem.de/wp-content/uploads/2021/01/IKEM_Kurzstudie_Wasserstoff_Farbenlehre.pdf (accessed Dec 18, 2022).

[6] Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J., Few, S. Future cost and performance of water electrolysis: An expert elicitation study. *Int. J. Hydrog. Energy* 2017, 42, 30470–30492. DOI.10.1016/j.ijhydene.2017.10.045

[7] Patonia, A., Poudineh, R. Cost-competetive green hydrogen: how to lower the cost of electrolysers? *Oxford Institute for Energy Studies*. Jan 2022. ISBN 978-1-78467-193-8.