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Review Article

The investment costs of electrolysis – A comparison of cost studies from the past 30 years

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ABSTRACT

Water electrolysis is a promising technology for storing surplus energy from intermittent renewable energy sources in the form of hydrogen. The future investment costs of water electrolysis represent one key challenge for a hydrogen-based energy system. In this work, a literature review was conducted to evaluate the published data on investment costs and learning rates for PEM and alkaline electrolyzers from the 1990s until 2017 and the years beyond. The collected data are adjusted for inflation and specified in $€_{2017}$ per kW-output using the higher heating value (HHV). R&D efforts have led to impressive cost reductions in the observed period, especially for PEM technology, while cost reductions for alkaline technology have also been decent. The overall spread of the cost estimations in the 1990s was in a range between 306 and 4748 $€_{2017}/kW_{HHV\text{-}Output}$. Today's estimations for future investment costs (through 2030) for both technologies are narrowed towards values of 397 and 955 $€_{2017}/kW_{HHV\text{-}Output}$. Higher automation, mass production, larger cell areas, market penetration and technology development will all have a further impact on the investment costs.

Contents

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Introduction

On a global scale, the total amount of installed renewable capacity in 2015 was 785 GW (665 GW in 2014) without hydro, and 1849 GW (1701 GW in 2014) with it. In the power sector, the new installed capacities of renewables in 2015 were higher than the added capacity from all fossil fuels combined worldwide. In total, in 2015 23.7% of the global electricity was already supplied by renewable power sources, of which 16.6% was from hydropower [1].

On the one hand, power from hydro, wind, solar and other renewable energy sources has the potential to reduce CO_2 emissions by replacing fossil fuels and, additionally, dependence on imported energy [2].

On the other hand, this rapid increase of renewable capacities presents new challenges concerning energy supply reliability, distributed generation management, the storage and utilization of surplus energy and, especially, electrical grid expansion [3,4]. Current electrical grids were built when the generation of electricity was centralized and designed for predictable electrical output, and not for the variable power generation that characterizes renewable sources [4].

The inherent fluctuation or intermittence of renewable power can cause a surplus or a deficit of electricity in the power grid. A surplus of wind energy stresses the electric grid and a re-dispatch of wind power plants is therefore necessary to keep grid frequency in balance. Due to such shutdowns, about 400 GWh of electrical energy was lost in Germany in 2011. In contrast to a surplus, there are phases in which more electricity is consumed than can be produced by renewables. To overcome such drawbacks, storage capacities are needed to store the surplus energy. This is especially crucial in Germany where, according to forecasts, when the transition from conventional energy production to renewables is complete, around 40 TWh of storage capacity will be necessary [5].

Batteries are not suitable for long-term storage due to their high self-discharge rate and low current densities [6]. Disadvantages of pumped storage plants include effects on the landscape, such as through dams and water basins [7].

Hydrogen produced by water electrolysis from excess renewable energy is a solution to the aforementioned challenges and is the key technology of the “Power-to-Gas” [8] and “Power-to-Fuel” concepts [9–11]. The hydrogen produced can be converted back into electricity in times with low energy production [12]. Thus, hydrogen can be used as a long-term storage medium for excess energy [12]. Further application possibilities for this hydrogen could be fuel cell vehicles in the transport sector, the injection of hydrogen into a gas grid for heating, as a feedstock for chemicals, or as a reduction agent in the steel production [13–20].

For the production of hydrogen by water electrolysis, PEM electrolysis, alkaline electrolysis and SOEs are considered. PEM electrolysis is a promising technology, since higher current densities (>2 A/cm^2), gas purity, compact system design and dynamic operation are enabled by this technology. In particular, dynamic operation makes PEM electrolysis suitable for intermittent power inputs [21].

Recently, the dynamic behavior of a 6 MW PEM electrolyzer was demonstrated at the Energiepark Mainz, Germany. In a test, the plant ramped up from 0 to 6 MW in 1 min and 10 s (86 kW/s). Values above 200 kW/s are the actual ramp speed and in the range of 0–4 MW, even higher speeds are feasible [22].

While solid oxide electrolyzers remain in the R&D stage, alkaline electrolyzers are commercially-available and considered a mature technology [3]. Typical properties associated with alkaline systems are low current densities (0.2–0.5 A/cm^2) and low partial load range (20–40%) [21]. Nevertheless, newer membranes and system designs could help to overcome these drawbacks [23,24].

The fact that water electrolysis attracted interest as a sustainable way to store energy and that countries such as Germany will need large storage capacities, it is necessary to investigate the economics of water electrolysis techniques.

In order to make renewably-produced hydrogen from water electrolysis competitive with other production methods, apart from the electricity costs and electrolyzer efficiency, the investment costs per kW are important [25]. Investment costs and the efficiency of electrolysis plants are not only relevant for power to hydrogen plants, but also have a major impact on “Power-to-Fuel” processes [9]. This study focuses on the investment costs but we point out that the OPEX costs have also a major impact on the hydrogen price.

The future investment costs of water electrolysis will be one key challenge for a hydrogen-based energy system. Low investment costs are beneficial for consumers and plant operators, and would affect the hydrogen price positively. Therefore, the accessibility of predefined cost goals is an important issue for water electrolysis and other hydrogen technologies, in addition to aspects such as the efficiency, dynamics and durability of an electrolysis plant. In the literature, cost data for PEM and alkaline plants from manufacturers or from research institutes can be found. A literature review was conducted to evaluate the published data on investment costs from the 1990s through 2017. This overview will help manufacturers, researchers and governmental institutions gain insight into the development of electrolysis costs and thus evaluate cost projections. Additionally, this study should help make the published cost data comparable. The collected data were adjusted for inflation, transferred to $€_{2017}$ and are summarized in Table 1 and Figs. 3 and 4, respectively.

Literature review on electrolyzer investment costs

This section deals with the electrolyzer costs published by manufacturers and researchers in studies, papers and presentations. Data from the manufacturer side are only available to a very limited extent. Nevertheless, cost data from this perspective were obtained. In contrast to manufacturer-based cost data, which are available to a limited extent, more data from researchers are available. Like the cost data from manufacturers, the cost estimations made by experts are also listed in Table 1.

In 1992, Jónsson et al. [26] conducted a feasibility study on using geothermal energy for the production of hydrogen by means of various electrolysis technologies. At this time, many

Table 1 – Cost estimations for PEM and alkaline electrolyzers. The collected data are adjusted for inflation and specified in the last column in €$_{2017}$/kW$_{Output\text{-}HHV}$. Bold values were calculated with information given in the reference. The data per kW$_{Output\text{-}HHV}$ are plotted in Figs. 3 and 4. Bold values show the reader which values were calculated by the author with information given in the reference.

Publication	Type	Publication date	Estimation for year	(€, \$, Yen)/kW	In €$_{2017}$/ kW$_{HHV\text{-}output}$
[26] Values include: plant equipment, buildings of plants, office buildings, miscellaneous and the interests during construction (2 years)	Atmospheric Alkal. Norsk Hydro 100 MW Input: $\mu_{System,HHV}$ = 78%, T = 80 °C; Details in previous section	1992	1992	**666 $\$_{1992}/kW_{Input}$ 853 $\$_{1992}/kW_{HHV\text{-}Ouput}$ 1007 $\$_{1992}/kW_{LHV\text{-}Output}$**	1581
	Pressurized Alk. Lurgi S556 100 MW Input: $\mu_{Total,HHV}$ = 81%, T = 90 °C, p = 31 bar; Details in previous section	1992	1992	**856 $\$_{1992}/kW_{Input}$ 1057 $\$_{1992}/kW_{HHV\text{-}Ouput}$ 1247 $\$_{1992}/kW_{LHV\text{-}Output}$**	1960
[27]: Possible costs for home electrolyzers; Price for full systems; Estimations by NREL	PEM-system: $\mu_{System,HHV}$ = 94%; Cost estimation by Thomas et al.; Value was very optimistic; Not in Fig. 3	1995	2020	1700 $\$_{1995}/kW_{Input}$ **1808 $\$_{1995}/kW_{HHV\text{-}Output}$ 2130 $\$_{1995}/kW_{LHV\text{-}Output}$**	3113
	PEM-system: $\mu_{System,HHV}$ = 94%; DOE cost projection	1995	2000–2005; Value token for 2000	2000 $\$_{1995}/kW_{Input}$ **2222 $\$_{1995}/kW_{HHV\text{-}Output}$ 2622 $\$_{1995}/kW_{LHV\text{-}Output}$**	3825
	PEM-system $\mu_{System,HHV}$ = 87%; DOE cost projection	1995	1995	2400 $\$_{1995}/kW_{Input}$ **2758 $\$_{1995}/kW_{HHV\text{-}Output}$ 3255 $\$_{1995}/kW_{LHV\text{-}Output}$**	4748
	Alkal.-system: $\mu_{System,HHV}$ = 90%; Cost estimation by Thomas et al. based on very large production	1995	2020	300 $\$_{1995}/kW_{Input}$ **333 $\$_{1995}/kW_{HHV\text{-}Output}$ 395 $\$_{1995}/kW_{LHV\text{-}Output}$**	573
	Alkal.-system: $\mu_{System,HHV}$ = 88%; DOE cost projection	1995	2000–2005; Value token for 2000	350 $\$_{1995}/kW_{Input}$ **437 $\$_{1995}/kW_{HHV\text{-}Output}$ 469 $\$_{1995}/kW_{LHV\text{-}Output}$**	752
	Alkal.-system: $\mu_{System,HHV}$ = 80%; DOE cost projection	1995	1995	500 $\$_{1995}/kW_{Input}$ **625 $\$_{1995}/kW_{HHV\text{-}Output}$ 737 $\$_{1995}/kW_{LHV\text{-}Output}$**	1076
Hamilton Standard in [27]: Estimation based on sales of 100,000 electrolyzer per year	PEM-system: 0.011 MW with 12 pounds per day hydrogen; $\mu_{System,HHV}$ = 80%	1995	1995	**226 $\$_{1995}/kW_{Input}$ 283 $\$_{1995}/kW_{HHV\text{-}Output}$** 330 $\$_{1995}/kW_{LHV\text{-}Output}$	487
Los Alamos in [27]: Estimation for General Electric PEM electrolyzer	PEM-system: 530 MW plant; $\mu_{System,HHV}$ = 80%	1995	1995	**278 $\$_{1995}/kW_{Input}$ 348 $\$_{1995}/kW_{HHV\text{-}Output}$** 410 $\$_{1995}/kW_{LHV\text{-}Output}$	599
General Electric in [27]	PEM-system: 50 MW electrolyzer; $\mu_{System,HHV}$ = 80%	1995	1995	**142 $\$_{1995}/kW_{Input}$ 178 $\$_{1995}/kW_{HHV\text{-}Output}$** 210 \$1995/$kW_{LHV\text{-}Output}$	306
Lawrence Livermore National Laboratory in [27]:	PEM-system: Home electrolyzer 0.0025 MW; $\mu_{System,HHV}$ = 80%	1995	1995	**994 $\$_{1995}/kW_{Input}$ 1243 $\$_{1995}/kW_{HHV\text{-}Output}$** 1480 $\$_{1995}/kW_{LHV\text{-}Output}$	2140
Stone Webster [27]	PEM-system: 17.5 MW plant; $\mu_{System,HHV}$ = 67.5%	1995	1995	**485 $\$_{1995}/kW_{Input}$ 719 $\$_{1995}/kW_{HHV\text{-}Output}$** 850 $\$_{1995}/kW_{LHV\text{-}Output}$	1238
Los Alamos in [27]	Alkal.-system: 530 MW plant with 260 tons per day; $\mu_{System,HHV}$ = 81%	1995	1995	**916 $\$_{1995}/kW_{Input}$ 1146 $\$_{1995}/kW_{HHV\text{-}Output}$** 1350 $\$_{1995}/kW_{LHV\text{-}Output}$	1973
Lawrence Livermore National Laboratory in [27]: Electrolyzer to supply a 300-car-per-day gas station in small quantities	Alkal.-system: Estimation for a 2.5 MW system; $\mu_{System,HHV}$ = 81%	1995	1995	**867 $\$_{1995}/kW_{Input}$ 1070 $\$_{1995}/kW_{HHV\text{-}Output}$** 1275 $\$_{1995}/kW_{LHV\text{-}Output}$	1842
Princeton in [27]: Estimation by Princeton University	Unipolar alk.-system: Estimation for 10 MW; $\mu_{System,HHV}$ = 81%	1995	1995	**394 $\$_{1995}/kW_{Input}$ 486 $\$_{1995}/kW_{HHV\text{-}Output}$** 580 $\$_{1995}/kW_{LHV\text{-}Output}$	837
Corporation Toronto in [27]: Electrolyser Corporation of Toronto world's largest producer of commerical electrolyzer at this time	Unipolar alkal-.system: Estimation for 100 MW Input; $\mu_{System,HHV}$ = 80%	1995	1995	**395 $\$_{1995}/kW_{Input}$ 494 $\$_{1995}/kW_{HHV\text{-}Output}$** 590 $\$_{1995}/kW_{LHV\text{-}Output}$	850

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Table 1 – (continued)

Publication	Type	Publication date	Estimation for year	(€, $, Yen)/kW	In $€_{2017}$/ $kW_{HHV\text{-}output}$
Fluor Daniel in [27] value includes: compressor, storage tanks, facility and engineering	Unipolar alkal.-system: Estimation for 100 MW_{Input} and 21,788 Nm^3/h; $\mu_{System,HHV} = 71\%$	1995	1995	968 $\$_{1995}/kW_{Input}$ 1363 $\$_{1995}/kW_{HHV\text{-}Output}$ 1600 $\$_{1995}/kW_{LHV\text{-}Output}$	2347
[56]	PEM-system: Estimation for an electrolysis unit 1170 kgH_2/day; $\mu_{System,HHV} = 80\%$	1996	1996	460 $\$_{1996}/kW_{Input}$ 567 $\$_{1996}/kW_{HHV\text{-}Output}$ 667 $\$_{1996}/kW_{LHV\text{-}Output}$	952
	Alkal.-system: Estimation for an electrolysis unit 1170 kgH_2/day; $\mu_{System,HHV} = 80\%$	1996	1996	744 $\$_{1996}/kW_{Input}$ 930 $\$_{1996}/kW_{HHV\text{-}Output}$ 1094 $\$_{1996}/kW_{LHV\text{-}Output}$	1562
[28]	Alkal.-system: Range for 100 MW plant based on information from industry; $\mu_{System,HHV} = 70\%$; Efficiency assumed by author	1997	1997	~600 $\$_{1997}/kW_{Input}$ 857 $\$_{1997}/kW_{HHV\text{-}Output}$ 1000 $\$_{1997}/kW_{LHV\text{-}Output}$	1404
Audus in [28]: For a 1000 MW plant in Norway	Alkal.-system: Actual cost for plant built in Norway, 278,000 Nm^3/h, ~1000 MW (HHV); $\mu_{System,HHV} = 70\%$; Efficiency assumed by author	1911	1997	~622 $\$_{1997}/kW_{Input}$ ~888 $\$_{1997}/kW_{HHV\text{-}Output}$ ~1036 $\$_{1997}/kW_{LHV\text{-}Output}$	1455
[70]	Alkal.-system: Assumtption for 2 MW system; $\mu_{System,HHV} = 82\%$	1998	2000	600 $\$_{1998}/kW_{Input}$ 731 $\$_{1998}/kW_{HHV\text{-}Output}$ 1094 $\$1_{998}/kW_{LHV\text{-}Output}$	1065
[70]: Projection for year 2010	Alkal.-system: Assumtption for 2 MW system; $\mu_{System,HHV} = 87\%$	1998	2010	300 $\$_{1998}/kW_{Input}$ 344 $\$_{1998}/kW_{HHV\text{-}Output}$ 406 $\$1_{998}/kW_{LHV\text{-}Output}$	501
[30, 31]: More details in previous section	Cost of Protons "HOGEN 40" 6 kW system; No efficiency reported in reference; Value not in Fig. 4	2000	2000	6333 $\$_{2000}/kW_{Input}$	9636 $\$_{2000}/kW_{Input}$
	Cost of Protons "HOGEN 380" 60 kW system; No efficiency reported in reference; Value not in Fig. 4	2000	2000	2000 $\$_{2000}/kW_{Input}$	3043 $\$_{2000}/kW_{Input}$
[71]	Alkal.-system: Costs at that time; $\mu_{System,HHV} = 73\%$	2000	2000	730 $€_{2000}/kW_{Input}$ 1000 $€_{2000}/kW_{HHV\text{-}Output}$ 1140 $€_{2000}/kW_{LHV\text{-}Output}$	1277
[71]	Alkal.-system: Cost projection for 2020; $\mu_{System,HHV} = 77\%$	2000	2020	539 $€_{2000}/kW_{Input}$ 700 $€_{2000}/kW_{HHV\text{-}Output}$ 831 $€_{2000}/kW_{LHV\text{-}Output}$	894
[49]: Equation based on power law; detailed description in previous section 50 Nm^3/h 15 kA/m^2	PEM-system: According to Oi and Wada's equation for 50 Nm^3/h 15 kA/m^3; $\mu_{System,HHV} = 70\%$; Efficiency assumed by author	2003	2003	125335 Yen_{2003}/kW_{Input} 179050 $Yen_{2003}/kW_{HHV\text{-}Output}$ 208891 $Yen_{2003}/kW_{LHV\text{-}Output}$	1446
[49]: Equation based on power law; detailed description in previous section	PEM-system: According to Oi and Wada's equation for 200 Nm^3/h 15 $kA/m^{2;}$ $\mu_{System,HHV} = 70\%$; Efficiency assumed by author	2003	2003	93679 Yen_{2003}/kW_{Input} 133827 $Yen_{2003}/kW_{HHV\text{-}Output}$ 156131 Yen2003/$kW_{LHV\text{-}Output}$	1081
[72]: Overview on production methods for hydrogen and their economics	PEM-system: Cost target by Padro for large volume production of 100,000 units per year for a 25 kg per day electrolyzer; $\mu_{System,HHV} = 70\%$; Efficiency assumed by author	2004	Goal	300 $\$_{2004}/kW_{Input}$ 428 $\$_{2004}/kW_{HHV\text{-}Output}$ 500 $\$_{2004}/kW_{LHV\text{-}Output}$	590
	PEM-system: DOE cost goal for a 2.5 kg per day electrolyzer; $\mu_{System,HHV} = 70\%$; Efficiency assumed by author	2004	Goal	1200 $\$_{2004}/kW_{Input}$ 1714 $\$_{2004}/kW_{HHV\text{-}Output}$ 2000 $\$_{2004}/kW_{LHV\text{-}Output}$	2363
	PEM-system: DOE cost goal for a 25 kg per day electrolyzer in volumes of 10,000 units per year; Not in Fig. 4	2004	Goal	600 $\$_{2004}/kW_{Input}$	827 $€/kW_{Input}$
	PEM-system: Cost at that time; Value not in Fig. 4	2004	Current	3500 $\$_{2004}/kW_{Input}$	4825 $€/kW_{Input}$

[73]: Presents a cost function for large scale hydrogen plants	Type not specified; Costs for a plant with 50,000 Nm^3/h; **Assumed efficiency by author $\mu_{system,HHV}$ = 70%**	2005	2005	470 €$_{2005}$/kW$_{Input}$ **671 €$_{2005}$/kW$_{HHV-Output}$ 783 €$_{2005}$/kW$_{LHV-Output}$**	902
[45]: Costs based on manufacturer information in the period from 2003 to 2005	PEM-system: Value for a 0.8 Nm^3/h electrolyzer; No efficiency reported in reference; Value not in Fig. 3; **Assumed efficiency by author $\mu_{system,HHV}$ = 70%;** Value not in Fig. 4	2004	2004	**21782 €$_{2005}$/kW$_{Input}$ 31117 €$_{2005}$/kW$_{HHV-Output}$ 36303 €$_{2005}$/kW$_{LHV-Output}$**	37521
	PEM-system: Value for a 10 Nm^3/h electrolyzer; No efficiency reported in reference; Value not in Fig. 3; **Assumed efficiency by author $\mu_{system,HHV}$ = 70%;** Value not in Fig. 4	2004	2004	**5932 €$_{2005}$/kW$_{Input}$ 8474 €$_{2005}$/kW$_{HHV-Output}$ 9886 €$_{2005}$/kW$_{LHV-Output}$**	10218
	Alkal.-system: Value for a 120 Nm^3/h electrolyzer; No efficiency reported in reference; **Assumed efficiency by author $\mu_{system,HHV}$ = 70%**	2004	2004	**1443 €$_{2005}$/kW$_{Input}$ 2062 €$_{2005}$/kW$_{HHV-Output}$ 2405 €$_{2005}$/kW$_{LHV-Output}$**	2486
	Alkal.-system: Cost projection for 2020; No efficiency reported in reference; **Assumed efficiency by author $\mu_{system,HHV}$ = 70%**	2004	2020	**805 €$_{2005}$/kW$_{Input}$ 1151 €$_{2005}$/kW$_{HHV-Output}$ 1342 €$_{2005}$/kW$_{LHV-Output}$**	1388
[74]	Alkal.-system: Value for atmospheric; pressurized 20% more expensive; **$\mu_{system,HHV}$ = ~80%**	2008	2008	800-1500 €$_{2008}$/kW$_{Input}$; Assumed 1150 €$_{2008}$/kW$_{Input}$ **1437 €$_{2008}$/kW$_{HHV-Output}$ 1691 €$_{2008}$/kW$_{LHV-Output}$**	1636
	PEM-system: Values for capacity range between 1 and 10 Nm^3/h; **$\mu_{system,HHV}$ = ~80%**	2008	2008	2000-6000 €$_{2008}$/kW$_{Input}$ -> Assumed 4000 €$_{2008}$/kW$_{Input}$ **5000 €$_{2008}$/kW$_{HHV-Output}$ 5882 €$_{2008}$/kW$_{LHV-Output}$**	5692
	Alkal.-system: Projection; $\mu_{system,HHV}$ > 83%	2008	2020	<500 €$_{2008}$/kW$_{Input}$ for > 1 MW; **602 €$_{2008}$/kW$_{HHV-Output}$ 714 €$_{2008}$/kW$_{LHV-Output}$**	685
	PEM-sytem: Projection; $\mu_{system,HHV}$ > 83%	2008	2020	<1000 €$_{2008}$/kW$_{Input}$ for > 500 kW; **1204 €$_{2008}$/kW$_{HHV-Output}$ 1428 €$_{2008}$/kW$_{LHV-Output}$**	1371
[24]: Manufacturer based costs; detailed description of values in previous section	Alkal.-system: Atmospheric electrolyzer with 500 Nm^3/h capacity; No efficiency reported in value; **Assumed efficiency by author $\mu_{system,HHV}$ = 75%**	2011	2011	1000 €$_{2011}$/kW$_{Input}$ **1333 €$_{2011}$/kW$_{HHV-Output}$ 1587 €$_{2011}$/kW$_{LHV-Output}$**	1453
[50]	PEM-system: Calculation for optimized PEM electrolyzer with capability of threefold overload; **Assumed efficiency by author $\mu_{system,HHV}$ = 80% in 2030**	2012	2030	586 €$_{2012}$/kW$_{Input}$ **732 €$_{2012}$/kW$_{HHV-Output}$ 861 €$_{2012}$/kW$_{LHV-Output}$**	787
	Alkal.-system: Calculation for optimized alkal. Electrolyzer; **Assumed efficiency by author $\mu_{system,HHV}$ = 80% in 2030**	2012	2030	586 €$_{2012}$/kW$_{Input}$ **732 €$_{2012}$/kW$_{HHV-Output}$ 861 €$_{2012}$/kW$_{LHV-Output}$**	787
[35]	PEM-sytem: Commercially available stack; $\mu_{Stack,HHV}$ > 87%; Cost for large scale production; Value not in Fig. 4	2013	2013	350 \$$_{2013}$/kW$_{Input}$ for commercial Stack	386 €/kW$_{Input}$
	PEM-system: Cost goal for the commercially available stack; Value not in Fig. 4	2013	2013+	<300 \$$_{2013+}$/kW$_{input}$ for Stack	331 €/kW$_{Input}$

(continued on next page)

Table 1 – (*continued*)

Publication	Type	Publication date	Estimation for year	(€, $, Yen)/kW	In €$_{2017}$/kW$_{HHV-output}$
[49]: Values include power supply, system control, gas drying (purity above 99,4%). Detailled descritption in section *Literature review on electrolyzer investment cost; value also used in* [78]	Alkal.-system: $\mu_{system,HHV}$ = 72%	2014	2014	1100 €$_{2014}$/kW$_{Input}$ **1572 €$_{2014}$/kW$_{HHV-Output}$ 1807 €$_{2014}$/kW$_{LHV-Output}$**	1641
	Alkal.-system: $\mu_{system,HHV}$ = 74%	2014	2015	930 €$_{2014}$/kW$_{Input}$ **1256 €$_{2014}$/kW$_{HHV-Output}$ 1487 €$_{2014}$/kW$_{LHV-Output}$**	1311
	Alkal.-system: $\mu_{system,HHV}$ = 75%	2014	2020	630 €$_{2014}$/kW$_{Input}$ **840 €$_{2014}$/kW$_{HHV-Output}$ 994 €$_{2014}$/kW$_{LHV-Output}$**	877
	Alkal.-system: $\mu_{system,HHV}$ = 77%	2014	2025	610 €$_{2014}$/kW$_{Input}$ **792 €$_{2014}$/kW$_{HHV-Output}$ 937 €$_{2014}$/kW$_{LHV-Output}$**	827
	Alkal.-system: $\mu_{system,HHV}$ = 78%	2014	2030	580 €$_{2014}$/kW$_{Input}$ **743 €$_{2014}$/kW$_{HHV-Output}$ 879 €$_{2014}$/kW$_{LHV-Output}$**	765
	PEM-system: $\mu_{system,HHV}$ = 69%	2014	2014	2090 €$_{2014}$/kW$_{Input}$ **3028 €$_{2014}$/kW$_{HHV-Output}$ 3584 €$_{2014}$/kW$_{LHV-Output}$**	3162
	PEM.-system: $\mu_{system,HHV}$ = 75%	2014	2015	1570 €$_{2014}$/kW$_{Input}$ **2093 €$_{2014}$/kW$_{HHV-Output}$ 2477 €$_{2014}$/kW$_{LHV-Output}$**	2185
	PEM-system: $\mu_{system,HHV}$ = 82%	2014	2020	1000 €$_{2014}$/kW$_{Input}$ **1219 €$_{2014}$/kW$_{HHV-Output}$ 1443 €$_{2014}$/kW$_{LHV-Output}$**	1273
	PEM-system: $\mu_{system,HHV}$ = 82%	2014	2025	870 €$_{2014}$/kW$_{Input}$ **1060 €$_{2014}$/kW$_{HHV-Output}$ 1255 €$_{2014}$/kW$_{LHV-Output}$**	1107
	PEM-system: $\mu_{system,HHV}$ = 83%	2014	2030	760 €$_{2014}$/kW$_{Input}$ **915 €$_{2014}$/kW$_{HHV-Output}$ 1083 €$_{2014}$/kW$_{LHV-Output}$**	955
[5]: Detailled descritption in previous section	Alkali.-system: $\mu_{system,HHV}$ = 68%	2014	2017	**1328 €$_{2014}$/kW$_{Input}$ 1952 €$_{2014}$/kW$_{HHV-Output}$ 2304 €$_{2014}$/kW$_{LHV-Output}$**	2038
	Alkali.-system: $\mu_{system,HHV}$ = 68–72% -> 70%	2014	2030	**608** €$_{2014}$/kW$_{Input}$ **868 €$_{2014}$/kW$_{HHV-Output}$ 1024 €$_{2014}$/kW$_{LHV-Output}$**	906
	PEM-system: $\mu_{system,HHV}$ = 69%	2014	2017	**1034 €$_{2014}$/kW$_{Input}$ 1498 €$_{2014}$/kW$_{HHV-Output}$ 1768 €$_{2014}$/kW$_{LHV-Output}$**	1564
	PEM-system: $\mu_{system,HHV}$ = 84%	2014	2030	**324 €$_{2014}$/kW$_{Input}$ 386 €$_{2014}$/kW$_{HHV-Output}$ 459 €$_{2014}$/kW$_{LHV-Output}$**	397
[75]: Similar approach to Oi et al. [35]	Alkal.-system: 1 MW; **Assumed efficiency by author $\mu_{system,HHV}$ = 75%**	2015	2015+	900 €$_{2015}$/kW$_{Input}$ **1200 €$_{2015}$/kW$_{Input}$ 1428 €$_{2015}$/kW$_{Input}$**	1235
	Alkal.-system: 200 MW; **Assumed efficiency by author $\mu_{system,HHV}$ = 80%**	2015	2015+	300 €$_{2015}$/kW$_{Input}$ **375 €$_{2015}$/kW$_{Input}$ 441 €$_{2015}$/kW$_{Input}$**	386
[46,47]: Detailled descritption in previous section	Alkal.-system: Value taken from chart published by NEL in 2014; The value applies to a 44 MW pressurized system and includes installation and commissioning; No efficiency reported in reference; **Assumed efficiency by author $\mu_{system,HHV}$ = 75%**	2014	2014	648 €$_{2014}$/kW$_{Input}$ **864 €$_{2014}$/kW$_{Input}$ 1028 €$_{2014}$/kW$_{Input}$**	902
[76]	PEM-system: Cost goal for PEM systems; **Assumed efficiency by author $\mu_{system,HHV}$ = 80%**	2015	2015+	500 €$_{2015}$/kW$_{Input}$ **625 €$_{2015}$/kW$_{HHV-Output}$ 735 €$_{2015}$/kW$_{HHV-Output}$**	643
[14]	Type not specified; Outlook for 2050; **Assumed efficiency by author $\mu_{system,HHV}$ = 85% in 2050; value not in figures**	2015	2050	140-260 €$_{2015}$/kW$_{Input}$ -> 260 Token as value; **260 €$_{2015}$/kW$_{Input}$ 305 €$_{2015}$/kW$_{HHV-Output}$ 361 €$_{2017}$/kW$_{LHV-Output}$**	314
[77]: Current goal	Target for forecourt production; Uninstalled costs for electrolyzer; System efficiency 44 kWh/kg	2017	2020	300 \$$_{2017}$/kW$_{Input}$ **337 €$_{2017}$/kW$_{HHV-Output}$ 400 €$_{2017}$/kW$_{LHV-Output}$**	337

manufacturers of bipolar alkaline electrolyzers already existed. Norsk Hydro, Lurgi, De Norra, Teledyne Isotopes, ABB and Hydrogen Systems were listed as manufacturers of alkaline systems, whereas for PEM electrolyzers only General Electric is mentioned. SOE technology was only at the R&D stage. Jónsson et al.'s cost information were obtained from Norsk Hydro for an atmospheric alkaline electrolyzer (electrolyzer type: Norsk Hydro) and from Lurgi for a pressurized alkaline electrolyzer (electrolyzer type: Lurgi S556). The costs for the SOE system were provided by Dornier and constituted a hypothetical estimation for a unit using 100 MW electric power (electrolyzer type: HOT-ELLY). The specific capital costs in $\$_{1992}$ of these three plants with 100 MW electric input are given as 853 $\$_{1992}/kW_{Output\text{-}HHV}$, 1057 $\$_{1992}/kW_{Output\text{-}HHV}$ and 801 $\$_{1992}/kW_{Output\text{-}HHV}$ for the HOT-ELLY electrolyzer. This includes the costs of the plant equipment, buildings of plants, office buildings, miscellaneous expenses and interest during construction (2 years) [26]. Details on the efficiency of the systems can be found in Table 1.

In 1995, Thomas et al. [27] presented several estimations by experts from institutions and industry. These cost estimations enclose small and large-sized PEM and alkaline electrolyzers and cover the period from 1977 to 1995. The estimations from Thomas et al. are summarized with the assumptions made by experts in Table 1. Thomas et al. converted the collected cost data into $\$_{1995}$ and to $\$_{1995}/kW_{Output\text{-}LHV}$. The paper also gives insight into the manufacturing volumes of small and large-sized electrolyzers in the 1990s. The authors [27] also note that the manufacturing volumes of large electrolyzer systems were on the order of one or two per year in the 1990s. Based on information obtained from Electrolyser of Canada and Teledyne Brown of Maryland, the sale of small-sized electrolyzers for industrial and research laboratories were on the order of few dozen per year. During this time, the Packard Instrument Company manufactured roughly 1000 small PEM electrolyzers at production rates of 1 L per minute [27].

In the 1990s Proton, which was founded in 1996 [28] as a spin-off from Hamilton Standard [29], Siemens, ABB and de Nora engaged in the active development of PEM electrolysis technology [29].

In 1998, the Department of Energy (DOE) awarded a program to Proton Energy System Inc. (Proton On-Site) with the goal of converting excess renewable power into hydrogen and making the hydrogen available for conversion back into power. Additionally, the costs for the capability had to be less than 1000 $\$_{2000}/kW_{Input}$ in the near term and 500 $\$_{2000}/kW_{Input}$ within 10 years. The program was divided into a demonstration phase (Phase 1) in which Proton demonstrated a functioning renewable hydrogen utility system and a second phase, with the goal of reducing the costs of the hydrogen generator family by 50% in two years and further into the years beyond. The costs of Proton's HOGEN 40 6 kW_{Input} system were $\$_{2000}$ 38,000 (6333 $\$_{2000}/kW_{Input}$) and for its HOGEN 380 60 kW_{Input} system $\$_{2000}$, 120,000 (2000 $\$_{2000}/kW_{Input}$). Proton's ten year cost projections for these two systems were 800 $\$_{2000}/kW_{Input}$ and 500 $\$_{2000}/kW_{Input}$ [30,31].

According to several publications by Proton and Giner [32–35], both companies reduced stack capital costs in the period from 2001 to 2011 by 81% (>2800 $\$/kW_{Input}$ in 2001 to less than 400 $\$/kW_{Input}$ in 2011) [32,33]. Cost reductions were achieved through lower anode loading (50% reduction) [33], lower cathode loading (90% reduction) [33], design of the cell [33,34], part count reduction (41 parts per cell in 2006, 10 parts per cell in 2012) [34,35] control board development [30,31] and 90% cost reduction of MEAs by fabricating chemically-etched supports [33]. In this period, the efficiency of the stack was increased from 70 $\%_{HHV}$ to 88 $\%_{HHV}$ and the specific energy consumption was decreased from 56 kWh/kg_{H2} to 45 kWh/kg_{H2} [32]. Additionally, membrane thickness was decreased from 0.254 mm to 0.076 mm and the operating temperature increased from 50 °C to 80 °C [32]. In 2010, Proton had over 1300 PEM units operating in the field [36].

Additional cost reductions are expected through further technical improvement of flow fields, the MEA, labor, economies of scale, higher automation, improved quality control methods, higher operating temperatures, larger cell areas and higher current densities [36–39].

A promising approach for cost reductions on the flow fields is presented by Gago et al. [40,41] and Lettenmeier et al. [42,43]. Gago et al. and Lettenmeier et al. use vacuum plasma spraying to coat a stainless steel substrate with titanium powder. For further protection of the titanium a niobium layer is coated on the titanium surface using physical vapor deposition [43]. Gago et al. report costs of 2,9 $\$_{2015}$ for large scale production and coating of a 1000 cm^2 surface [40]. The presented value does not include the costs of the physical vapor deposition process. For MEAs the company Solvicore, in cooperation with the NOW GmbH, has developed an MEA manufacturing process for fuel cells that can also be applied to mass production [44]. This process can be also adapted for electrolyzer technology.

In 2002, the EU commissioned a consortium of ife (Institute for Energy Technology), CRES (Centre for Renewable Energy Sources), Econnect and Trama Tecno Ambiental to analyze the potential of hydrogen in Stand-Alone Power Systems (H-SAPS). The aim of the study was to understand the technical and economic potential of Hydrogen-Stand-Alone Power Systems (H-SAPS) that are based on local renewable energy sources to replace those based on fossil fuels. The focus of the study was on small and medium-sized electrolyzers of up to several hundred kW. SAPS are used in areas that are not connected to the regional or national power grid and use fossil fuels for power generation [45].

From 2001 to 2003, the consortium collected cost data for small and medium-sized electrolyzers from industry in Europe and the USA. The cost data were collected via questionnaires, are based on 10 different suppliers and cover a capacity range between 1 and 120 Nm^3/h. From these 10 suppliers, only 1 was a supplier of PEM systems. PEM systems were in the price range between 110,000 $€_{2004}/Nm^3/h$ for a 0.8 Nm^3/h system and 30,000 $€_{2004}/Nm^3/h$ for a 10 Nm^3/h system. This corresponds to specific costs of 31,117$€_{2004}/kW_{HHV\text{-}Output}$ and 8474$€_{2004}/kW_{HHV\text{-}Output}$.for an assumed system efficiency of 70$\%_{HHV}$ The alkaline systems were approaching a price limit of 7300 $€_{2004}/(Nm^3/h)$ (for a 120 Nm^3/h system), which corresponds to specific costs of 2062 $€_{2004}/kW_{HHV\text{-}Output}$ (assumed efficiency 70$\%_{HHV}$). Hence, the expert group assumed that medium to large-scale electrolyzers would be dominated by alkaline systems. Similar to the cost data, a

SWOT analysis was conducted based on information from questionnaires to evaluate the obstacles to the introduction of hydrogen technologies into the energy market. The technological immaturity of fuel cells and PEM electrolyzers, low availability and high cost of small electrolyzers, few complete system deliveries, lack of after-sales support, weak supply network and procurement costs were pointed out as weaknesses and barriers for the market penetration of these technologies [45]. Smolinka et al. [24] published manufacturer-based investment costs for alkaline and PEM systems. The data were collected in the period from 2004 to 2009 with offers from industry and price inquiries. The costs apply only to the actual electrolysis system at the level of individual production (no scale effects), without mechanical compressors or storage units. No information was available on the manufacturer's margin. The investment costs decrease significantly by up to 100 Nm^3/h for pressurized and ambient systems, and then only marginal cost reductions can be observed. According to this survey, the specific investment costs of a pressurized system with a production capacity of 500 Nm^3/h are ~34% higher than for an ambient system. The investment costs for the PEM systems were obtained through telephone inquiries from Proton Energy Systems (Proton On-Site) and are limited to small-sized electrolyzers in the range between 0.5 Nm^3/h (14,285 $€_{2011}/kW_{HHV\text{-}Output}$, assumed efficiency 70%) and 6 Nm^3/h (2857 $€_{2011}/kW_{HHV\text{-}Output}$, assumed efficiency 70%) [24].

Fig. 1 shows the investment costs data from Smolinka et al. and the EU study [24,45] in [$€/kW_{Input}$] for ambient and pressurized alkaline electrolyzers over the produced hydrogen in [Nm^3/h].

From the figure, it can be seen that the investment costs decrease significantly to about 100 Nm^3/h and then, only marginal cost reductions can be recorded. The strong cost reduction in the small capacity range can be attributed to the peripheral costs, which are independent of capacity [24].

Similar data were published by NEL in 2014 for alkaline systems, but for a wider plant capacity range (1 MW_{Input} to 44 MW_{Input}). Fig. 2 shows the CAPEX values in [$€/kW_{Input}$] for.

Ambient and pressurized plants with and without installation and commissioning. According to NEL's data, the CAPEX for pressurized plants are ~20% higher than for ambient plants. CAPEX is reduced by more than 60% when plant size is increased from 250 kW_{Input} to 2.5 MW_{Input} and then approaches a value of 516 $€_{2014}/kW_{Input}$ for the ambient plant [46,47].

From the figure, it can be seen that the investment costs decrease significantly to about 100 Nm^3/h, and only then can marginal cost reductions be recorded. The strong cost reduction in the small capacity range can be attributed to the peripheral costs, which are independent of the capacity [24].

In 2014, a consortium of Fraunhofer ISE, DLR, Ludwig Bölkow Systemtechnik and KBB Underground Technologies

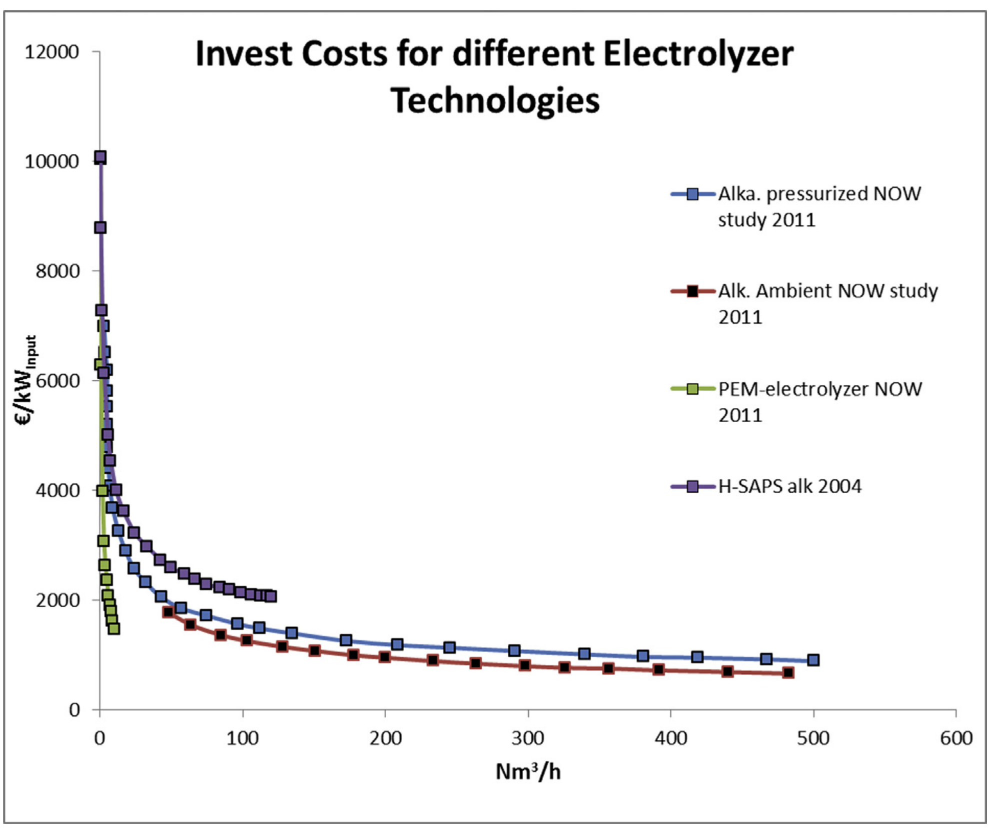

Fig. 1 – Development of investment costs in $€/kW_{Input}$ for electrolysis plants over the produced amount of hydrogen in Nm^3/h [24,45]. The values from the year 2004 [45] were obtained via questionnaires from industry and are higher than the values presented in 2011 in the NOW study [24], which were obtained through offers in the period from 2004 to 2009. The data for PEM systems are based on information from Proton OnSite, and are presented in the NOW study [24].

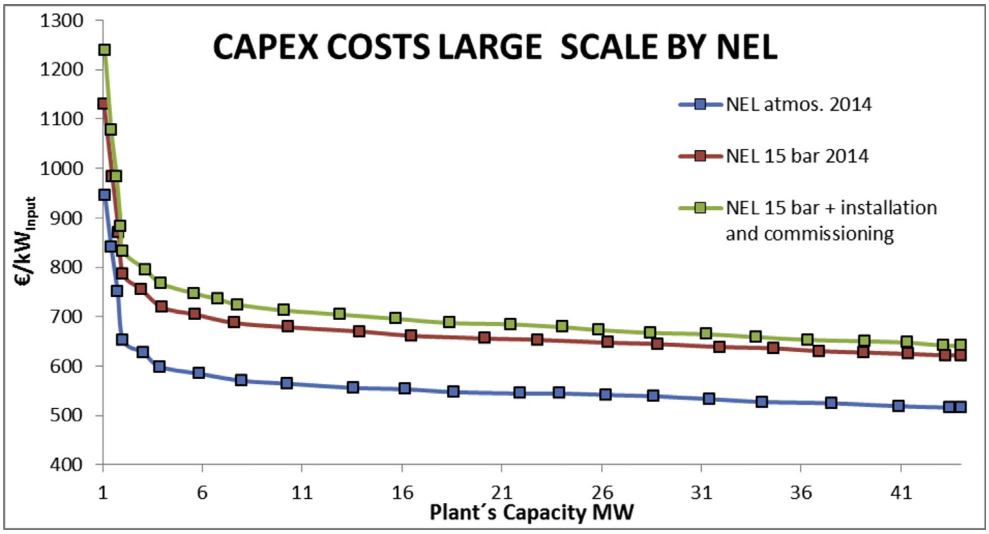

Fig. 2 – Development of CAPEX costs for large alkaline electrolyzers over plant capacity (1–44 MW_{Input}) according to NEL. According to this data, pressurized plants are ~20% higher than ambient plants. CAPEX decreases significantly in the small MW range [41,42].

published a government-supported study, the so-called PlanDelyKad study [5]. One aim of this was the evaluation of the technical and economic potential of alkaline and PEM technology with a view to its application on a large scale in the short term, as well as in the long term. To estimate the costs, a 5 MW_{Input} and 100 MW_{Input} system were designed for both technologies. The 5 MW_{Input} plant presents the state of the art in 2016/2017, while the 100 MW_{Input} plant is an outlook for 2030. A detailed cost model of the investment (CAPEX) and running costs (OPEX) is presented for the afore-mentioned concepts. For the determination and estimation of the expected costs of the alkaline system, industrial offers were collected. For the 100 MW_{Input} plant, therefore, the offer was supplemented by own estimates to take technical development until 2030 into account. According to the calculations, the investment costs are 5.333 million $€_{2014}$ (1070 $€_{2014}$/kW_{Input}, 1573 $€_{2014}$/$kW_{HHV\text{-}Output}$) for the 5 MW_{Input} electrolytic system and 52.139 million $€_{2014}$ (520 $€_{2014}$/kW_{Input}, 742 $€_{2014}$/$kW_{HHV\text{-}Output}$) for the 100 MW_{Input} system, respectively. This includes the stack, transformer, rectifier, control and process visualization, KOH management, gas analytics, ambient air monitoring, water treatment, hydrogen purification, fittings and pipes, spare parts, assembly supervision and commissioning, scrubbers, H_2 compressor and copper cables. An additional 1.31 million $€_{2014}$ (5 MW_{Input} system, with a building area of 953 m^2) and 8.66 million $€_{2014}$ (100 MW_{Input} system, with a building area of 6300 m^2) were calculated for the housing of the systems by KBB. The annual OPEX costs for the 5 MW_{Input} plant are 7% and based on information from a manufacturer. Due to the technical approach and higher lifespan, the group expects annual operating costs of 2% for the 100 MW_{Input} plant in 2030 [5,48].

Two approaches were used to determine and estimate investment costs for the two PEM systems. While the cost data of the peripheral components, housing and costs for planning were provided by several manufacturers, a separate cost model was used for the calculation of the stack costs. The investment costs for the 5 MW_{Input} electrolytic system are given with 4.785 million $€_{2014}$ (957 $€_{2014}$/kW_{Input}, 1386 $€_{2014}$/$kW_{HHV\text{-}Output}$) and 30.5 million $€_{2014}$ for the 100 MW_{Input} (305 $€_{2014}$/kW_{Input}, 363 $€_{2014}$/$kW_{HHV\text{-}Ouput}$) system, respectively. This includes the stack, water treatment, transformer, deoxygenation reactor, rectifier, heat exchanger (condenser), condensation separators, cooling water, air cooler, circulation pump, gas-water separator for the anode and cathode, demineralization cartridge, fittings and pipes and a 20% surcharge to cover research costs and accrue a profit. Similar to the alkaline systems, an additional 389,125 $€_{2014}$ (5 MW_{Input} system, building area 283 m^2) and 1.991 million $€_{2014}$ (100 MW_{Input} system, building area 1448 m^2) were calculated for the housing of the PEM systems by KBB. The annual OPEX are given with 2% (5 MW_{Input}) and 1.5% (100 MW_{Input}), respectively [5,48].

While in the PlanDelyKaD study a detailed cost model is used to estimate the possible costs of electrolyzers, the FCHJU study [49] gathered data from academic and industrial organizations. The aim of the study is to understand the conditions under which water electrolyzers play a role in the energy system, identify technology gaps and barriers to deployment and to propose research topics for RD&D that could achieve those targets. With the gathered data from the literature and stakeholders, the FCHJU constructed trend lines that capture the expected developments for costs by experts and manufacturers from 2013 through 2030. The ranges of the expected costs for alkaline and PEM systems are bounded by an optimistic and a conservative outlook. The cost estimations include power supply, system control and gas drying and exclude grid connection, external compression, external purification and hydrogen storage. For alkaline technology, which is regarded as a mature technology, FCHJU expects that much of the cost reduction will come from improved supply chain and higher volume production, while for the PEM

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electrolyzer, technological innovation will be an important contributor to cost reductions. According to the study, the main focus for technology innovation should be on the flow fields, the catalyst for OER (oxygen evolution reaction) and HER (hydrogen evolution reaction) and membranes. High volume production, supply chain development and technology innovation are generally seen as important routes for cost reduction [44]. Specific balance of plant components designed for the electrolysis process are considered to have a positive impact on the investment costs and the system dynamics [25,49,50]. The FCHJU updated this data for PEM and alkaline systems for different systems sizes in 2017 [51]. This study also includes cost data on compressors, filling centers, operating costs as well as mobile and stationary storage systems for electrolyzers [51].

In 2013, the Forschungszentrum Jülich performed a study [50] on optimizing electrolysis technology and the investment costs, operating and control costs to investigate the impact of these parameters on the costs of produced hydrogen. For the year 2030 and for optimized electrolyzers in the megawatt range, Mergel et al. calculated for PEM and alkaline technology investments costs of ~585 $€_{2013}/kW_{Input}$, but with the option of operating PEM electrolysis with threefold overload [50]. According to Mergel et al., these would constitute a quarter of the investment costs for PEM systems in 2012 (2000 $€_{2012}/kW_{Input}$) [52]. The capability of running PEM electrolyzers in overload was recently shown at the Energiepark Mainz, Germany [22].

For 2030, Stolten [53] predicts investment costs of 500 $€_{2013}/kW_{Input}$ for PEM systems. Stolten assumes that Germany will need installed electrolyzer capacities of 28 GW and full market integration will be achieved.

Oi et al.'s [54] approach for the plant costs of PEM electrolyzers is based on the power law (Eq. (1)). This law describes plant costs as a function of plant capacity.

$$P_c[\$,€,¥,\ldots] = (P_{cap})^n[kg/d, Nm^3/d,\ldots] \quad (1)$$

P_c = Plant costs, P_{cap} = Plants production capacity, n = cost exponent [55].

$$\text{Oi et al.}: P_c[¥] = 3.2*10^6*(P_{cap}[Nm^3/h])^{0.79}*(A[kA/m^2])^{-0.32} \quad (2)$$

P_c = Plant costs, P_{cap} = Plants production capacity, A = Rating Current Density.

In general, the cost exponent n has a value between 0.6 and 0.8, depending on the plant. Based on confirmed information from sources in industry in 2009, the DOE reports a value between 0.6 and 0.7 for capacities of up to about 1000 kg/day [25]. The exponent gives an economy of scale because plant costs increase less proportionally than the plant's capacity [25]. P_C describes the plant costs, P_{Cap}, the plant capacity and A stands for the rating current density [54].

Oi et al.'s equation covers a capacity range from 50 to 200 Nm^3/h. According to their approach, the costs of PEM electrolyzers do not generally change in the range of the current density above 15 kA/m^2. Hence, Oi et al. determine the rating current density as 15 kA/m^2 [54]. Smolinka et al. [24] extrapolated Oi et al.'s equation to production rates below <50 Nm^3/h to investigate if there is a fit to the gathered data from Proton OnSite for production rates between 0.5 and 10 Nm^3/h. There was no fit to the data that were gathered through telephone inquiries from Proton OnSite.

In the period from 2008 to 2013, as part of a DOE-funded project, Giner [35] developed a cost-effective PEM electrolyzer. The goal of the project was to increase the efficiency of PEM electrolyzers and reduce the electrolyzer stack costs. Giner developed low-cost components and fabrication methods that have led to 60% cost reductions at the stack level. Membranes and cell components of the stack can exceed 60,000 h of operating time. Giner estimated that the cost of this stack in large-scale manufacturing of up to 1500 MW/year will be less than 350 $\$_{2013}/kW_{Input}$. Assuming that the stack accounts for 50% of the overall costs, this would correspond to ~700 $\$_{2013}/kW_{Input}$ for the whole system. Giner's goal is to reduce the cost below 300 $\$_{2013}/kW_{Input}$. The developed stack is commercially available [35].

Mayyas et al. [56] presented in 2017 preliminary analysis on PEM electrolyzer stack costs for a 200 MW_{Input} and 1 MW_{Input} stack. The authors assume in their analysis an annual production rate of 50,000 stacks. For the 200 kW_{Input} stack, the costs drop from 500 $\$_{2017}/kW_{Input}$ at a production rate of 10 stacks per year to ~50 $\$_{2017}/kW_{Input}$ at a production rate of 1000 units per year. Between 10,000 and 50,000 units per year no change in the costs can be observed. The costs for the 1 MW_{Input} stack drop from ~140 $\$_{2017}/kW_{Input}$ at a production rate of 10 stacks per year to less than 40 $\$_{2017}/kW_{Input}$ at 1000 units per year. Likewise, no change in the costs can be observed between 10,000 and 50,000.

Learning curves for electrolyzers

The basic idea of learning or experience curve is that the time or cost of performing a task decreases by a constant fraction with every doubling of production as a worker gains experience [57–60]. Wright developed in 1936 the first experience curves for the amount of labor hours spent for production of aircrafts. Wright's model is widely used to determine the historical cost reductions of technologies. Learning curves are empirically expressed and in Wright's model it is written as [57]:

$$Y(x) = aX^b \quad (3)$$

where:

Y = the cumulative average time (or cost) per unit
X = the cumulative number of units produced
a = the time (or cost) required to produce the first unit
b = slope of the function when plotted on log-log paper.
=log of the learning rate/log of 2

$$LR = 1 - 2^b (LR = \text{Learning Rate}) \quad (4)$$

$$PR = 1 - LR (PR = \text{Progress Ratio}) \quad (5)$$

The learning rate indicates the percentage by which the cost of production is reduced by every doubling [58,59,61]. The progress ratio indicates the fraction of the initial costs remaining after each doubling of production [58,59,62]. For electrolyzers Thomas et al. [27] and Rogner [63] estimated

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hypothetical learning curves in the 1990s. Thomas et al. estimated that the learning curve of PEM electrolyzers falls close to the one of black and white televisions with a learning curve of 90%, which corresponds to a learning rate of 10% with b being −0.15. Rogner [63] varied the parameter b to estimate the unit costs of alkaline electrolyzers for a cumulative electrolysis production of 200 GW at estimated base unit costs of $\$_{1998}$550 ±100 per kW. Schoots et al. [60] developed learning curves for the investment costs of electrolysis equipment, using cost data observed during the period from 1956 to 2007 and using the total cumulative global amount of hydrogen produced during this period by electrolysis. The evolved learning curve has a learning rate of 18% ± 13% but shows a poor fit to the data. Recently, Schmidt et al. [64] projected the future prices for several electrical energy storage technologies using experience curve. Schmidt et al. [64] updated the learning curve evolved by Schoots et al. [60] to project the prices for electrolysis at a cumulative installed capacity of 1000 GWh_{cap}. This updated learning curve has a learning rate of 18% ± 6%. To our knowledge these are the main sources that deal with learning curves.

A novel approach to develop learning curve for fuel cells, that can be adapted also to electrolyzers, is presented by Wei et al. [58,59]. The authors reviewed fuel cell and non-fuel cell cost studies to assess the novel of their approach. Wei et al. analyze in their study the stationary fuel cell markets in Japan and in the U.S. and find for the Japanese market a learning rate of 18% from 2005 to 2015. The overall cost reduction in this time was for the Japanese market 50%. In contrast to this, the SOFC systems in the California market have a flat (near-zero) learning rate. Japans fuel cell market benefits from more favorable market conditions, joint development, bigger market players and greater competition compared to the U.S. market. Wei et al. present a bottom-up direct manufacturing cost model to disaggregate the cost reductions into cost reduction from economies of scale, product design improvements and product performance improvements. Within their manufacturing cost model each stack component is modeled starting from equipment costs, operating costs, labor costs and factoring in material. Wei et al. apply their cost model and reported information in literature on product and design improvements to disaggregate the 50% cost reduction in the Japanese market into cost reduction from economies of scale, product design improvements and product performance improvements. Wei et al. recommend using similar approaches for other emerging technologies. This approach can be also adapted to electrolyzer technology. Main advantage is that the approach is analytically tractable.

Discussion of gathered investment costs

The gathered data in Table 1 and Figs. 3 and 4 are adjusted for inflation and transferred into €$_{2017}$ at an exchange rate of for $ to € of 1 and for ¥ to € of 0.0078. The annual inflation rate data were purchased from Statista and from Eurostat. According to Statista and Eurostat, the average inflation in the U.S. in the period from 1990 to 2017 was 2.5% [65], in the Euro area 1.45% [66,67] and in Japan 0.25% [66]. The investment costs in the last column in Table 1 are specified per unit of hydrogen output to consider the efficiency of the plant. Fig. 3 shows these cost projections for alkaline electrolyzers and Fig. 4 those for PEM. The shape of the data plot in Figs. 3 and 4, from 1990 to 2030, is slightly cuneiform. The spread of the estimations for alkaline systems in the 1990s was in a range between 873 and 2347 €$_{2017}$/$kW_{HHV\text{-}Output}$.

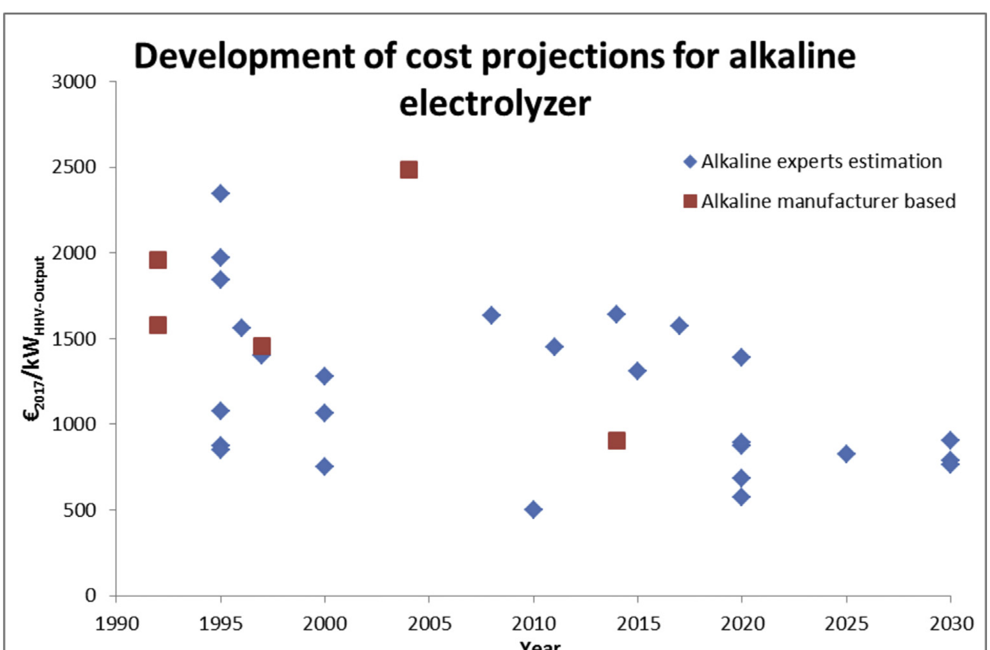

Fig. 3 – Development of expected alkaline electrolysis plant cost in €/$kW_{HHV\text{-}Output}$ according to experts and manufacturers in the past 30 years. Each data point is listed in Table 1. Figure shows a general trend of expectations.

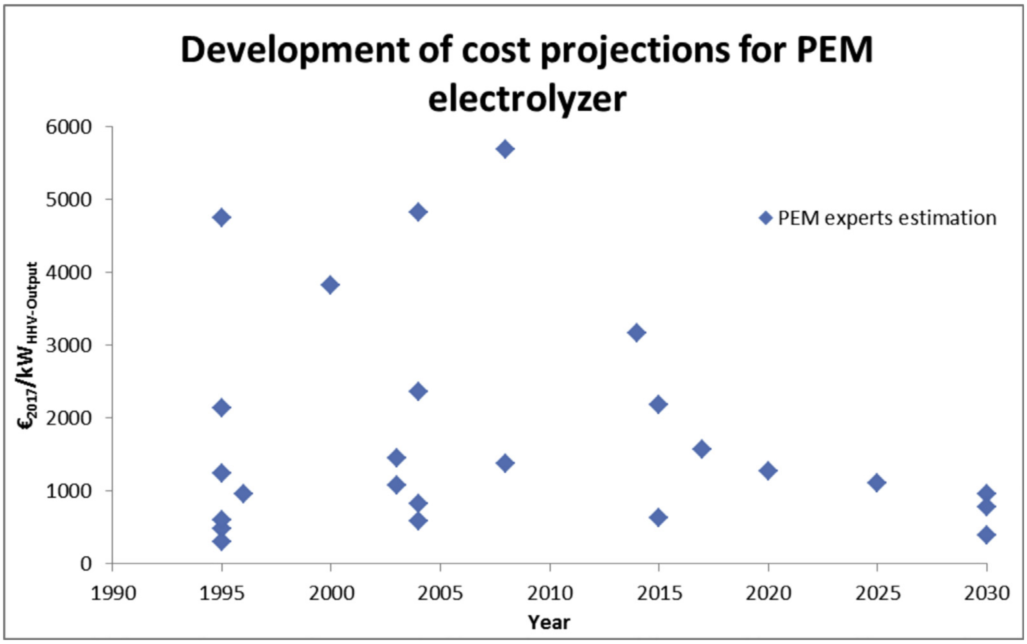

Fig. 4 – Development of expected PEM electrolysis plant cost in €/kW$_{HHV-Output}$ according to experts and manufacturers in the past 30 years. Each data point is listed in Table 1. Figure shows a general trend of expectations.

Today's estimations for the future investment costs of alkaline electrolysis plants (year 2030) are narrowed towards values of 787–906 €$_{2017}$/kW$_{HHV-Output}$. For PEM electrolyzers the spread in the 1990s was higher and in the range between 306 and 4748 €$_{2017}$/kW$_{HHV-Output}$. The future investment costs of PEM electrolysis plants for the year 2030 are narrowed towards 397 and 955 €$_{2017}$/kW$_{HHV-Output}$. From the reviewed studies only Smolinka et al. [5] expect that in 2030, the costs of PEM electrolyzers will drop below those of alkaline. Mergel et al. [52] and the FCJHU study [49] see the costs of both technologies in 2030 close to each other, but with the option of operating PEM electrolyzers.

For the alkaline technology, the cost reductions over the past decades are more moderate and manufacturer cost data and expert estimations show good agreement. This can be explained with the maturity of the alkaline technology. In contrast to the moderate changes of the alkaline technology, the cost reductions for PEM technology are impressive. We assume that the spread of the cost estimations in the 1990s for PEM electrolysis can be explained with the immaturity of PEM technology and, compared to alkaline electrolyzers, no MW plants were installed or made available. A handful of manufacturers, such as GE, Siemens and ABB, were offering small PEM systems of laboratory size. Today, companies like Proton, Giner and Siemens are offering PEM technology at the MW scale. For example, government policy in Germany has led to a shift from conventional to renewable power generation, and thereby to an increased interest in the water electrolysis technology and other storage technologies. In the period from 2000 to 2011, Proton and Giner reduced the specific capital cost of their stacks by more than 81% to less than 400 \$$_{2014}$/kW$_{Input}$. Assuming that the stack contributes to 50% of the overall costs, this would correspond to ~800 €$_{2014}$/kW$_{Input}$ for the entire system. This would already be competitive with today's costs for the alkaline systems, with 600–700 €$_{2014}$/kW$_{Input}$ [24,46,47]. Over the observed period, the costs of PEM systems approach the costs of alkaline systems. According to Pland-DelyKaD [5,31], the costs of PEM systems will drop below those of alkaline systems in 2030. The massive cost reductions were achieved through R&D, since no market penetration has occurred. Zoulias et al. expects that a market penetration will lead to cost reductions of 50% [68]. Rogner, meanwhile, points out that RD&D is a prerequisite to reducing the costs and improving the technology, but protected niche markets or government policy could generate a market pull of hydrogen technologies [63]. In a protected niche market, the costs for water electrolysis would be less important than the service provided [63].

We point out, that from the reviewed studies only Mayyas et al. [56] and to a wider extent Smolinka et al. [5] provided detailed information on manufacturing volume and system boundaries. We recommend that future cost projections should contain information about the manufacturing volume and about system parameters of the electrolyzer system like temperature, voltage, current density and pressure to make the projections comparable and transparent. Additionally, Wei et al.'s [58,59] bottom-up approach which is discussed in section 2.1 can be adapted to electrolyzer technology.

Conclusion

A literature review was conducted to determine the development of water electrolysis costs and published learning rates in the period from 1990 to 2017 and to forecast trends for the years beyond. Information was gathered from papers, studies

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and presentations from manufacturers and researchers. The collected cost data are specified per unit of hydrogen output to consider the efficiency of the plant.

R&D efforts have led to impressive cost reductions in the observed period, especially for the PEM technology, while cost reductions for alkaline technology have also been noteworthy. For alkaline technology, the spread of the estimations in the 1990s was in the range between 873 and 2347 $€_{2017}/kW_{HHV\text{-}Output}$. Today's estimations for the future investment costs (year 2030) are narrowed towards the values of 787 and 906 $€_{2017}/kW_{HHV\text{-}Output}$.

For PEM technology, the spread of the estimations in the 1990s was in the range between 306 and 4748 $€_{2017}/kW_{HHV\text{-}Output}$. Today's estimations for the future investment costs (year 2030) are narrowed towards the values of 397 and 955 $€_{2017}/kW_{HHV\text{-}Output}$.

Over the observed period, the cost estimates for PEM are approaching those of the alkaline.

Compared to the 1990s, when no PEM electrolyzers were available at the MW scale, today's manufacturers offer PEM systems in the MW range. Alkaline systems, by contrast, were already available in the MW range in the 1990s.For alkaline technology, which is regarded as a mature technology, experts expect that much of the cost reduction will come from improved supply chains and higher volume production, while for PEM, technology innovation will be an important contributor to cost reductions. Specifically, cost reductions for PEM systems are expected to come about as a result of further technical improvement of flow fields, the MEA and labor, with economics of scale, larger cell areas, higher automation and improved quality control methods.

As an outlook, it is recommended to further investigate the impact of manufacturing processes on electrolysis costs. Today, there is no mass production of electrolyzers and no market integration has occurred. Automation and standard manufacturing processes will be needed for successful market integration. This is especially the case for PEM electrolyzers, where different designs and concepts for MEAs, bipolar plates or GDL exist, and which should be easily producible. In this context, quality control methods for the detection of manufacturing defects in stack components will play an important role in avoiding failures of components during operation. This is especially the case for the MEA, where an integrated quality control in the manufacturing process would help to detect defects early on. The implementation of the six sigma quality method in to electrolysis manufacturing must be an aim. Furthermore, protected niche markets and incentive programs for electrolyzers would lead to an increase of market players and supply chain development, and in turn to the mass production of components in the electrolysis market.

Additionally, already existing bottom-up approaches as presented in this work, should be adapted to electrolyzer technology to determine stack manufacturing costs starting from equipment costs, operating costs, labor costs and factoring in material. Furthermore, future cost projections should contain information about the manufacturing volume and about operating parameters of the electrolyzer system like temperature, voltage, current density, pressure to make the projections comparable and transparent.

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